MEASUREMENT OF DIRECTIONAL EMITTANCE OF ROUGHENED ALUMINUM SURFACES

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MEASUREMENT OF DIRECTIONAL

EMITTANCE OF ROUGHENED ALUMINUM SURFACES

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NOMENCLATURE

English Letter Symbols

A - area ft^2

d - thermopile output

F - geometric shape factor

f - front face of thermopile

G - radiant energy flux, Btu/hr

i - radiant flux intensity, $\frac{Btu}{hr\text{-}ft^2\text{-unit solid angle}}$

T - temperature, °F or °R

Greek Letters

α - total absorptance

ϵ - total emittance

σ - Boltzmann Constant, $0.1713 \times 10^{-8} \frac{Btu}{hr - ft^2 - °R^4}$

ρ - total reflectance

θ - angle from normal

ϕ - azimuthal angle in the plane of the surface

Δ - K-3 potentiometer reading in microvolts

Subscripts

B - blackbody

G - guard blackbody

(Continued)

NOMENCLATURE (Concluded)

Subscripts

- h - hemisphere
- H - sample holder
- n - normal direction
- S - sample
- θ - angle from the normal
- ϕ - azimuthal angle in the plane of the surface

CHAPTER I

INTRODUCTION

Properties which are important in determination of the thermal radiation characteristic of surface are surface roughness, surface chemistry and the physical state of the surface layer of the material. The effects of these parameters are a function of wavelength of the emitted or reflected energy and surface temperature.

Surface roughness has long been known to affect the reflection characteristics of the material. The influence of the surface roughness on the reflection of monochromatic radiation in the specular-ray direction was investigated in reference (1). Monochromatic reflection measurements encompassing various directions in space (including the specular angle) were carried out in reference (2). Effects of surface roughness on the total hemispherical and specular reflectance of metallic surfaces are reported in reference (2).

It has been reported (Ref. 4) that the emittance of polished metals markedly increases by roughening the surface, by as much as a factor of 2 or 3 but for nonmetals and particularly white ceramic materials, emittance appears to be essentially independent of surface roughness (Ref. 4). The difference in the effect of surface roughness on emittance of metals as compared to nonmetals has been explained qualitatively on basis of the material involved. The phenomenon is explained better in terms of reflectance than in terms of emittance. This change in parameters is legitimate under certain conditions because, by Kirchhoff's law, the emittance is equal to the absorptance and hence, for opaque specimens, the emittance and reflectance sum to one. For details see reference (4).

Within the knowledge of the author, no prior systematic investigation seems to have been made of the effects of unidirectional roughness on directional emittance. Hence the primary purpose of this investigation is to determine the effects of surface temperature and surface roughness on the total directional and hemispherical emittance of a metal.

CHAPTER II

APPARATUS AND EQUIPMENT

The equipment and apparatus utilized in this experimental study will be described in detail in the following subsections. It is based on designs described in references (5, 6, and 7). A radiometer (Figure 1) is located centrally around which are placed the rest of the apparatus: heated blackbody, guard blackbody, sample holder and K-3 potentiometer assembly.

Radiometer

The radiometer is a device for collecting and measuring radiant energy and consists of a spherical mirror, thermopile detector and water cooled case. The radiant energy from a test surface enters through the aperture (A) of the radiometer and is collected by a five inch diameter aluminum surfaced mirror (B) which in turn focuses the energy onto the receiving surface of a thermopile (C) (Kipp and Zonen CA-1-650477). The fixed aperture of the thermopile and radiometer determines the size of the area viewed on the test surface.

In order to minimize the possibility of stray radiation from the outside striking the thermopile, the radiometer is painted black inside. The radiometer is also water-cooled, since this provides constant temperature environment which is essential to obtain stability of the measuring system. This constant temperature environment is found necessary, because without it the null-detector connected to the K-3 potentiometer shows shift in the reading caused by changing environmental conditions surrounding the thermopile.

K-3 Potentiometer and Accessories

The thermopile inside the radiometer is connected to a sensitive potentiometer (Type K-3 Universal Potentiometer, Leeds and Northrup, No. 7553-6, maximum sensitivity of $\pm$ 0.2 microvolts per division). The reading of the K-3 potentiometer gives an indication of the amount of the radiant energy impinging on the thermopile.

(a) Null-Detector - The null detector used was a Leeds and Northrup 9834 electronic D-C null detector. This detector has a maximum sensitivity of $\pm$ 0.3 microvolts per division and is matched to the K-3 potentiometer. The period for full scale deflection is less than two seconds and operates on 120 volts, 50/60 cycle line voltage.

(b) Standard Cell - A standard cell (The Eppley Laboratory) of 1.01920 voltage was used.

(c) Constant Voltage Supply - The 099034 constant voltage supply designed by Leeds and Northrup is used to stabilize the voltage to the null detector. The 099034 operates from line voltage and provides a constant d. c. voltage for the measuring circuit of the K-3 potentiometer.

The normal 117 volt, 60 cycle supply is reduced by step-down transformer in the unit and is converted to a d. c. voltage by rectification with silicon diodes. The d. c. voltage is regulated by a two-stage Zener diode network.

All leads from the thermopile to potentiometer are shielded. The shield is grounded which reduces any stray electrical pickup. Thus the potentiometer is completely shielded and has satisfactory stability. The assembly (K-3 potentiometer, null-detector) is also insensitive to mechanical vibrations.

Heated Blackbody

A heated blackbody is used as a reference source and consists of a cylindrical ceramic tube six inches long and two inches inside diameter with a one-half inch opening as shown in Figure 2. The inside of it was sprayed with black paint. The blackbody is heated by two separate Nichrome heaters (26 gage), one heater wrapped around the side and the second on back. The power input to each of these heaters is adjustable by a Variac so that a constant temperature inside can be obtained. The temperature distribution along the cylinder was measured by four thermocouples and could be adjusted to within $\pm$ 1°F of each other.

The blackbody is mounted inside a transite cylinder twelve inches long and eight inches outside diameter. The gap in between was filled with an insulator. The blackbody front facing the radiometer was water cooled and sprayed with black paint. This reduced stray radiation from entering the radiometer from other than the blackbody opening (D).

Guard Blackbody

A guard blackbody at the temperature of the radiometer and sample container was used as a reference for the measurements and as a measure of the blackbody radiation incident of the sample. It is a double walled copper tube six inches long and one and one-half inches in diameter, sprayed with black paint inside. The temperature of the guard is measured by a thermocouple attached to the inside wall.

Sample Heater and Holder

The sample holder and heater are shown in Figure 3. The size of the sample is 2" x 2" x $2\frac{1}{2}$" and both the sample and its holder rotate about a vertical axis. The axis of rotation passes through the viewed surface of the test sample, hence the sample can be viewed for various angles from the normal direction.

Sample Container

A water cooled container, Figure 1, painted black inside, surrounds the test sample and serves to provide a well defined radiation environment for the sample. The necessity of such a container is discussed in data analysis section of this thesis.

The heater was constructed by machining grooves $\frac{1}{8}$" deep and $\frac{1}{8}$" apart in a lava block which measures 2" x 2" and 1" thick. Nichrome heating wire (26 gage) was then wound into the grooves of the lava block. The windings were securely fastened by electric heater cement (Sauereisen Cement Co. No. 63 paste). A copper block of size 2" x 2" and $\frac{1}{2}$" thick was then placed in between the sample and the heater and served as temperature equalizer to give more uniform temperature across the sample. The thermocouple was fixed to the copper block to monitor its temperature. A small hole was drilled close to the surface of the sample and a thermocouple was installed. Since the test sample (in our case Al) has high thermal conductivity, the temperature gradient over a distance of $\frac{1}{32}$" is negligible.

The heat losses of the heater assembly were minimized by using transite mounting blocks on the top and the bottom of the sample, copper block, and heater as shown in Figure 2. After the test sample was installed, all adjustment of the angles and the temperature measurements could be made from outside.

Test Surfaces

Five pieces of 99.9% Aluminum (2" x 2" and $\frac{1}{2}$" thick) were well polished in the Georgia Institute of Technology Metallurgy Laboratory. Three of these pieces were roughened unidirectionally by using a range of silicon carbide sandpaper. The roughness was measured by surfindicator at various places on the surface (the size of the stylus used was 25 microns in diameter). After taking readings on these roughened surfaces they were coated with an evaporated aluminum film at the experimental Engineering Station of Georgia Tech. The thickness of aluminum film was approximately 0.2 microns.

To minimize surface chemistry effects, care was taken to use uniform handling and minimize the possibility of surface chemistry contamination.

Photomicrographs of three of the roughened surfaces are shown in Figure 4 where it is clearly seen that the surface roughness is principally unidirectional.

CHAPTER III

EXPERIMENTAL PROCEDURES

The following experimental steps were carried out for each test sample in the determination of the directional emittance of the sample.

Angle Adjustment

The angular adjustment of the system is made by replacing the sample with a plane mirror and thermopile with a small light source. The light path was located in the backward direction. The sample holder is then rotated till the light beam reflected from the mirror returns directly on itself. This is a normal direction of viewing. The small light source is removed from the thermopile case and the thermopile remounted. A pointer attached to the sample holder is then fixed to angle 0° position. The sample is then rotated to the extreme angle 82° on both sides and the two readings made with the K-3 potentiometer usually agreed within $\pm$ 1.0 microvolt.

Temperature Measurement

A millivolt potentiometer (Leeds and Northrup Co.) was used to measure the millivolts produced by the nine thermocouples used in the total assembly. An ice junction thermocouple was used as a reference. It was sealed in a small tube containing oil and placed in a thermoflask containing crushed ice and small quantity of distilled water.

Thermocouples made from the middle and two ends of the thermocouple wire spool and were calibrated at several temperatures. The results obtained and those in the conversion tables for thermocouples (Leeds and Northrup Co. 077989, Issue 4, pages 18-19) agreed within $\pm$ 0.5°F. All thermocouples used were made of copper and constantan.

CHAPTER IV

TEST PROCEDURE

(a) Adjust the blackbody voltage input to both heaters by using Variac to get the desired temperature. The voltage input was so adjusted by using Variac that all the four thermocouples located at different places inside the blackbody agreed within $\pm$ 1°F. The same procedure was used in all the tests.

(b) Adjust the voltage input by using the sample Variac to obtain the desired temperature of the test sample.

(c) The thermocouple reading was checked every hour and when the temperature change was less than 1°F in one hour period, the temperature was considered to be stabilized sufficiently as to permit a test to be made.

(d) The millivolt potentiometer is standardized and the emf's of all nine thermocouples recorded.

(e) The radiometer is then rotated about its vertical axis and sighted on the guard blackbody. The thermopile output is measured with the K-3 potentiometer and null detector. The reading is checked after about five minutes. When the two readings agree within $\pm$ 1.0 microvolt, a reading is recorded.

(f) The radiometer is then sighted on the heated blackbody. A reading is made with the K-3 potentiometer and null detector; after about five minutes the reading is checked. The two readings must agree within $\pm$ 1.0 microvolts.

(g) The radiometer is then sighted on the test sample. The same procedure is used as in (e) and (f) to measure the thermocouple output.

The sample is then rotated to angles 10°, 20°, 30°, 40°, 50°, 60°, 70°, 75°, 80°, 82°, and the procedure (g) repeated. After 82° the radiometer is rotated to the viewing position of the heated blackbody, and the guard blackbody and readings (e) and (f) were again confirmed.

(h) The K-3 potentiometer was standardized periodically.

(i) After this the voltage input to the sample heater was adjusted so that a new test sample temperature was obtained.

The sample deflections ΔS_θ is the difference between final reading obtained in the steps (g) and (e). The blackbody (heated) deflection, ΔB is the difference between the final readings obtained in the steps (f) and (e).

CHAPTER V

ANALYSIS OF DATA

The directional emittance is defined as the ratio of the radiant intensity leaving a surface at a given angle from the normal direction to the radiant intensity leaving a blackbody surface both at the same temperature.

$$\epsilon\ (\theta) = \frac{i_\theta}{i_B} \tag{1}$$

The test apparatus is designed so that the radiometer measures intensity rather than energy. This is so because the area viewed by the radiometer is always smaller than the emitting surface of the test sample. Intensity is defined as the radiant energy de per unit time and surface area contained in an infinitesimal solid angle $d\omega$ divided by the product of $d\omega$ and the cosine of the polar angle (θ)

$$I\ (\theta) = \frac{de}{d\omega \cos\theta} \tag{2}$$

Therefore, it is quite clear from this definition that the radiometer measures intensity.

The possible error in measuring emittance caused by the sample "seeing" part of the sample holder, thus adding to its amount of reflected energy to the thermopile, had to be carefully considered. This was accomplished by including all the additional energy term necessary in deriving equation for $\epsilon(\theta)$.

The radiative energy flux leaving heated blackbody at temperature T_B and arriving on unit area of the thermopile is determined by the solid angle intercepted by the aperture of the thermopile and is designated by

$$G_B = F\sigma T_B^4 \tag{3}$$

where F is the shape factor determined by the geometry of the system and σ is Stefan Boltzmann's constant.

Since the sample at a temperature T_S is completely surrounded by a black container at a temperature T_G the energy flux leaving its surface and arriving on a unit area of the thermopile is composed of emitted and reflected radiation for the surface

$$G_S = F\sigma\,(\epsilon_S T_S^4 + \rho_S T_G^4) \tag{4a}$$

where ϵ_S indicates the emittance and ρ_S the reflectance of the test specimen.

With the gray body assumption $\epsilon_S = 1 - \rho_S$, the following result is obtained from equation (4a)

$$G_S = F\sigma\,[\,\epsilon_S\,(T_S^4 - T_G^4) + T_G^4\,] \tag{4b}$$

The radiant energy flux leaving the guard blackbody at a temperature T_G and arriving on a unit area of the thermopile is

$$G_G = F\sigma T_G^4 \tag{5}$$

Subtracting equation (5) from equation (3) and (4b) and rearringing, results in the following expression for emittance

$$\epsilon_S = \left(\frac{T_B^4 - T_G^4}{T_S^4 - T_G^4}\right)\left(\frac{G_S - G_G}{G_B - G_G}\right) \tag{6}$$

The gray body assumption $\epsilon_S = 1 - \rho_S$ requires the sample is sufficiently thick (in our case thickness is $\frac{1}{2}$'') so that none of the impinging radiation leaves through the back of the surface and the emittance is not a function of wave length. Equation (4b) is a good approximation even when the last condition is not fulfilled; provided T_G is considerably smaller than T_S or when both the temperatures are nearly equal. The possible error on the end result of the variation of the emittance with the wavelength has to be decided from case to case.

It now remains to relate the radiation flux G to the thermopile deflection d. A heat balance is written on the front face of the thermopile for the condition that it is irradiated by energy coming from heated blackbody.

$$C_B G_B = \sigma\epsilon_f T_{fB}^4 - q_{rad} + q_{loss} \tag{7}$$

where

C - loss factor accounting for absorption of energy by CO_2 and water vapor in air and by aluminum surface mirror

ϵ_f - emittance of the thermopile surface

T_f - temperature of the exposed surface of the thermopile

q_{rad} - radiant energy absorbed by the thermopile originating from surrounding walls

q_{loss} - losses from the thermopile by convection and conduction

We write similar expressions when the thermopile is subjected to radiation from sample and guard blackbody

$$C_S G_S = \sigma \epsilon_f T_{f\,S}^4 - q_{rad} + q_{loss} \tag{8}$$

$$C_G G_G = \sigma \epsilon_f T_{f\,G}^4 - q_{rad} + q_{loss} \tag{9}$$

If the assumption is made that the decrease in intensity is equal in all cases ($C_S = C_G = C_B$) and that the environmental radiation to the thermopile and conduction and convection losses remain the same, one may write, combining equations (7), (8), and (9).

$$\frac{G_S - G_G}{G_B - G_G} = \frac{T_{f\,S}^4 - T_{f\,G}^4}{T_{f\,B}^4 \quad T_{f\,G}^4} = \frac{4T_{f\,G}^3 \,(T_{fS} - T_{fG})}{4T_{f\,G}^3 \,(T_{fB} - T_{fG})} \tag{10}$$

The error introduced in equation (10) by writing it in the form on the right, is quite small, with the numerator being in error approximately by the amount $1.5\,(T_{fS} - T_{fG})/T_{fG}$ and the denominator by a similar amount. The value $T_{fS} - T_{fG}$ is of the order of 1 to 2 degrees F; thereby giving the error of the order of 0.5% in the numerator and the denominator. The error in quotient is probably less than this amount.

The assumption $C_B = C_G = C_S$ may not be admissible in all cases, since absorption of carbon dioxide and water vapor depends upon the wave length. The radiometer may be flushed by nonabsorbing gas, but this was not done in any case of test runs since data appeared satisfactory and repeatable on different days as well.

The thermopile indication d is directly proportional to the differential between the front side temperature T_f of the thermopile and unexposed back side temperature T^*.

Therefore, when the radiometer is sighted at the heated black-body:

$$d_B = \text{const.}\ (T_{fB} - T^*) \tag{11}$$

Similarly when the radiometer is sighted at sample, and black-body guard:

$$d_S = \text{const.}\ (T_{fS} - T^*) \tag{12}$$

$$d_G = \text{const.}\ (T_{fG} - T^*) \tag{13}$$

By circulating water around the radiometer, the temperature T^* is maintained constant.

By substituting equation (11), (12), (13) in equation (10) and combining with equation (6) we arrive at the final relationship for emittance

$$\epsilon_S = \frac{(T_B^4 - T_G^4)}{(T_S^4 - T_G^4)} \quad \frac{(d_S - d_G)}{(d_B - d_G)} \tag{14}$$

$$= \frac{T_B^4 - T_G^4}{T_S^4 - T_G^4} \quad \frac{\Delta S}{\Delta B} \tag{15}$$

where $\Delta S = d_S - d_G$; $\Delta B = d_B - d_G$ and

$$\epsilon_S(\theta) = \frac{T_B^4 - T_G^4}{T_S^4 - T_G^4} \quad \frac{\Delta S_\theta}{\Delta B} \tag{16}$$

Thus the knowledge of three temperatures T_S, T_G, and T_B and the deflections $\Delta S_\theta = d_{S\theta} - d_G$; $\Delta B = d_B - d_G$ allow the calculation of the emittance of the test sample.

CHAPTER VI

RESULTS

The primary purpose of this study was to determine the effects of surface roughness on the directional emittance of a metal and to determine the total hemispherical emittance of roughened and well polished surface at two temperatures.

The actual testing program consists of 18 test runs on various samples. Two well polished and three surfaces of different root mean square surface roughnesses were tested at two different temperatures. All runs were recorded on data sheets and presented in Appendix B.

A well polished pure aluminum (99% Al) surface was used to establish the reliability and the accuracy of the equipment for the measurement of the directional emittance. The results of emittance as a function of angle of viewing (θ) from the surface normal are shown in Figure 5, compared to those reported by E. Eckert (ref. 8) on a similar surface and are seen to agree quite well. The present results are tabulated in Appendix B.

A piece of aluminum block (2'' x 2'' x $\frac{1}{2}$'') was coated with black paint and then with a deposit of acetylene soot. For such a surface the directional emittance should be constant up to an angle of approximately $\theta = 60°$. The result of the directional emittance as a function of angle from the normal checked satisfactory as shown in Figure 6.

The results of the directional emittance obtained on the polished aluminum and acetylene soot surfaces which agree with the previous works (ref. 7) and electromagnetic theory and established that the equipment worked satisfactory.

Well Polished Aluminum Samples

The directional emittance for two well polished samples (Nos. 2 and 5) at two different temperatures are tabulated in Appendix B and presented in Figures 7, 8, 9, and 10. These measurements on smooth surfaces will be used as a bases to compare the results of the roughened surfaces.

The well polished surfaces were coated with an evaporated film of aluminum (0.2 microns) to ascertain the effects of machine polishing technique on the emittance. The directional emittance was measured for one sample at two different temperatures and the results are tabulated in Appendix B and are shown in Figures 10, 12, and 16. The results show that the coated surface emit less energy in the normal direction and more energy at large angles from the normal. The lower emittance in the normal direction is attributed to surface preparation.

Roughened Surfaces

Directional emittance was measured for three samples (Nos. 1, 3, 6 with surface rough mean square roughnesses of 140 μ in., 120μin., 25μin., respectively) at two different temperatures and the results are tabulated in Appendix B. Graphs of the directional and relative directional emittance are presented in Appendixes C and D. A marked increase in directional emittance for the roughened samples over the polished sample is observed. The normal emittance for the roughened surface increased by a factor of two over the polish surface. For large angles of viewing, the emittance of the roughened surfaces approaches the values of the polished surface. The increase in emittance could be caused by a number of factors including roughness and surface stresses caused by the roughening process.

In order to eliminate any effects caused by surface damage the roughened surfaces were coated with an evaporated film of aluminum (0.2 microns) and the directional emittance measurements repeated at two different temperatures. The results are tabulated in Appendix B and graphs of directional and relative emittance are presented in Appendixes C and D. From the results obtained it appears that the increase in emittance is due to surface roughness and not caused by surface damage effects. The thickness of the evaporated film of aluminum is more than sufficient to hide the substrate material and eliminate any substrate effects.

Total Hemispherical Emittance

The total hemispherical emittance was calculated using the equation

$$\epsilon_h = \frac{1}{\pi} \int_0^{\pi/2} \int_0^{\pi/2} \epsilon(\theta, \phi) \sin\theta \cos\theta \, d\theta \, d\phi$$

$$\simeq 2 \times \text{Area Under Curve}$$

Graphs of $\epsilon_\theta \sin\theta \cos\theta$ against θ were plotted and area under curves were measured which when multiplied by two gives the hemispherical emittance. Graphs are shown in Appendix E and the values are present in Table 1. It is observed that hemispherical emittance depends both on the temperature as well as roughness.

A theoretical value for smooth surfaces of ratio of hemispherical to the normal emittance as a function of normal emittance is reported by Sparrow and Cess (ref. 9). The full lines indicate the theoretical curves for the electric conductors for the ratios of the extension coefficient to index of refraction (K/n) of 0 and 2. The experimental values obtained in this study are shown in Figure 20 and fairly good agreement exist between experimental results and those calculated theoretically from electromagnetic theory for K/n = 2.0.

A few remarks should be made in discussing the results and those predicted from theories.

As the temperature of a metal increases, the emittance of the surface should increase. In this experimental study, however, the temperature change was too small to observe any appreciable change in emittance of the surface. Also, any changes would be masked by the experimental errors in the data.

Theories for the emissive behavior of rough surfaces are lacking as in contrast to those developed for reflective behavior. Diffraction theory for slightly rough surfaces is such that the predicted spectral hemispherical emittance of rough surface will be identical to that of smooth one. However, in rougher surfaces the hemispherical emittance will increase and the effects of multiple reflections must be accounted for. Increases in directional emittance and hemispherical emittance as the surface roughness increases are observed in this study. This increase in emittance at all angles appears to be caused by surface roughness since several test samples were coated with Aluminum film of $0.2\,\mu$ and within the accuracy of the data the results were same.

The results show that the rougher the surface the greater is the emittance. This is probably due to increase in multiple reflection and a greater surface area to emit energy.

If we compared the normalized plot of $\frac{\epsilon(\theta)}{\epsilon_n}$ vs. θ for all the surfaces including polished sample within the accuracy of the data, all falls in a small band. Similar results were found by Rolling et al (Ref. 10) for isotropically roughened surfaces.

CHAPTER VII

CONCLUSIONS

The directional emittance obtained on various roughened test samples reveals that emittance follows somewhat the angular dependence of a polished metal surface. However, the results obtained in this study showed changes in surface emittance due to surface roughness.

It was observed that for aluminum, significant increase in normal emittance relative to the polished surface as roughness was increased from 25 microinch to 140 microinch.

Present theoretical treatment of interaction of electromagnetic energy with rough surfaces have not been used for predicting the emissive behavior of such surfaces. Present theories must be extended to include the effects of multiple reflections to the prediction of the distribution and magnitude of the emitted energy.

Directional values of emittance were observed to decrease with higher test temperatures for well polished surfaces but the directional values of emittance for roughened surfaces were observed to increase with higher test temperatures.

In order to determine if the increase in the emittance of the rough surfaces is due to damage in crystalline structure of the surface while roughing, two rough surfaces were coated with aluminum film and the results of this study shows no appreciable change in emittance. Hence, one may conclude that the increase in emittance is probably due to surface roughness alone.

Finally, directional values of emittance were observed to remain almost the same for rough surfaces even when coated with aluminum film of 0.2 micron but in case of well polished surfaces the directional value of emittance decreases when coated with Al film (0.2 μ). This is probably due to the fact that when well polished surfaces when coated with aluminum film, the surface finish improves.

Table 1. Hemispherical Emittance, Ratio of Hemispherical Emittance to the Normal Emittance for Test Samples

Sample Aluminum	Temperature	Hemispherical Emittance ϵ_h	Ratio of Hemispherical to the Normal Emittance $\frac{\epsilon_h}{\epsilon_n}$
No. 1(140 μin.)	210°F	.1026	1.1337
No. 1 Al film(0.2μ)	213°F	.1044	1.1578
No. 3(125 μin.)	210°F	.08869	1.1858
No. 3 Al film(0.2μ)	210°F	.08857	1.1888
No. 6 (25 μin.)	210°F	.08569	1.1611
No. 2 Well polished	212°F	.0655	1.1974
No. 2 Al film (0.2μ)	208°F	.06948	1.3413
No. 5 Well polished	210°F	.06702	1.227
No. 1 (140 μin.)	320°F	.121	1.1439
No. 1 Al film (0.2μ)	325°F	.114	1.152
No. 3 (125 μin.)	323°F	.1104	1.14
No. 3 Al film (0.2μ)	319°F	.1158	1.180
No. 6 (25 μin.)	322°F	.1012	1.219
No. 2 Well polished	323°F	.06056	1.367
No. 2 Al film (0.2μ)	320°F	.0596	1.182
No. 5 Well polished	326°F	.06255	1.224

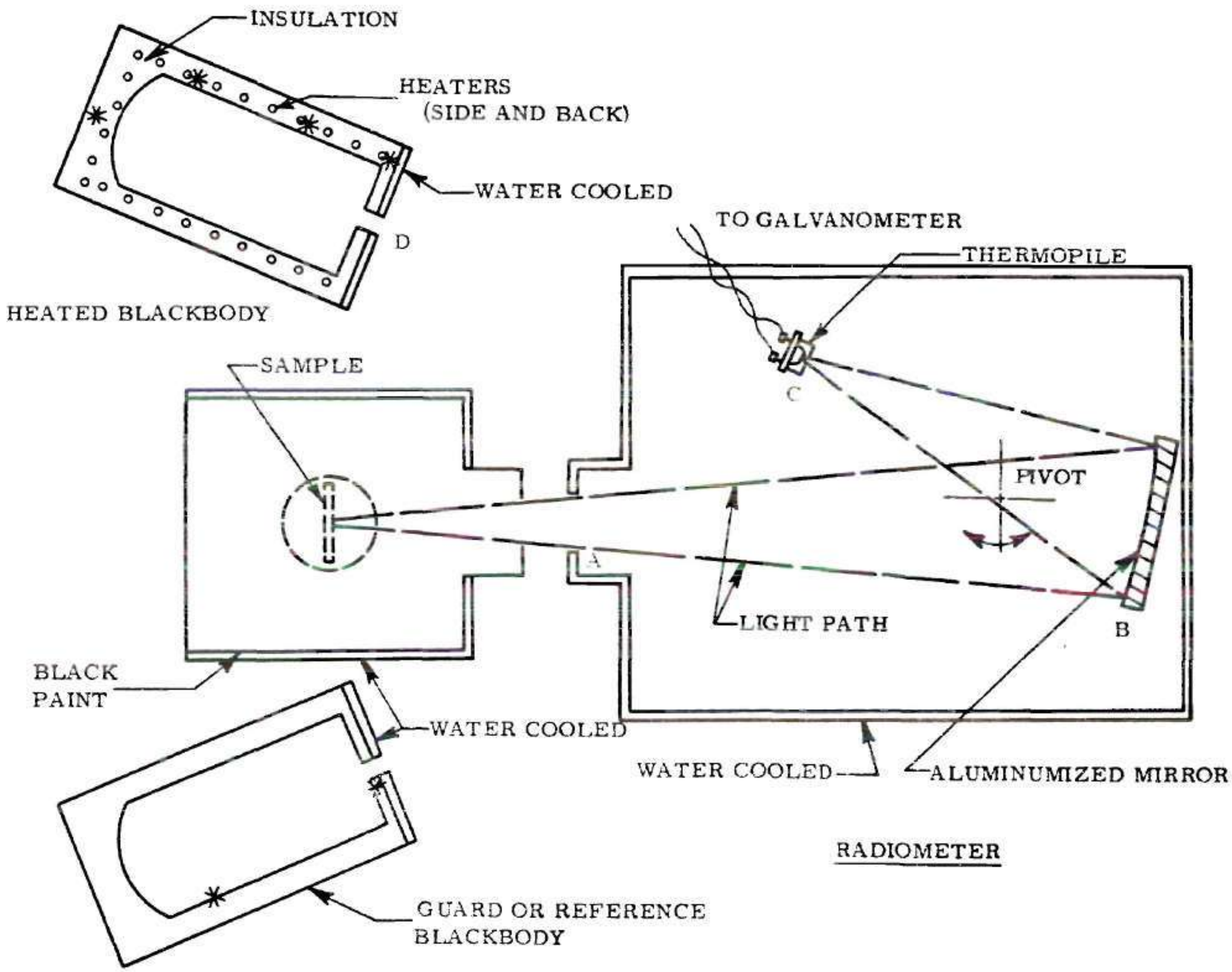


Figure 1. Directional Emittance Apparatus

* INDICATES THERMOCOUPLE POSITION

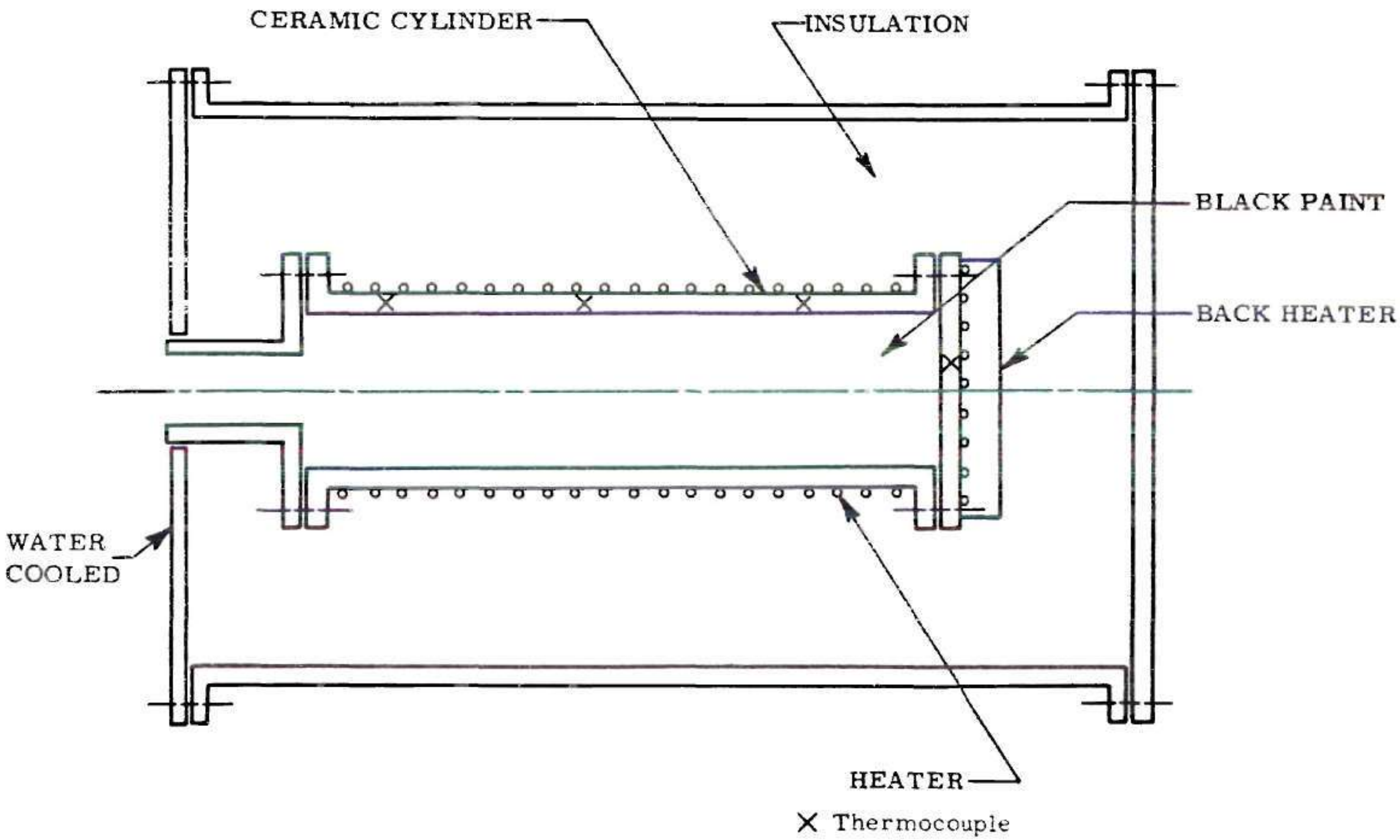


Figure 2. Blackbody (Black Painted Inside)

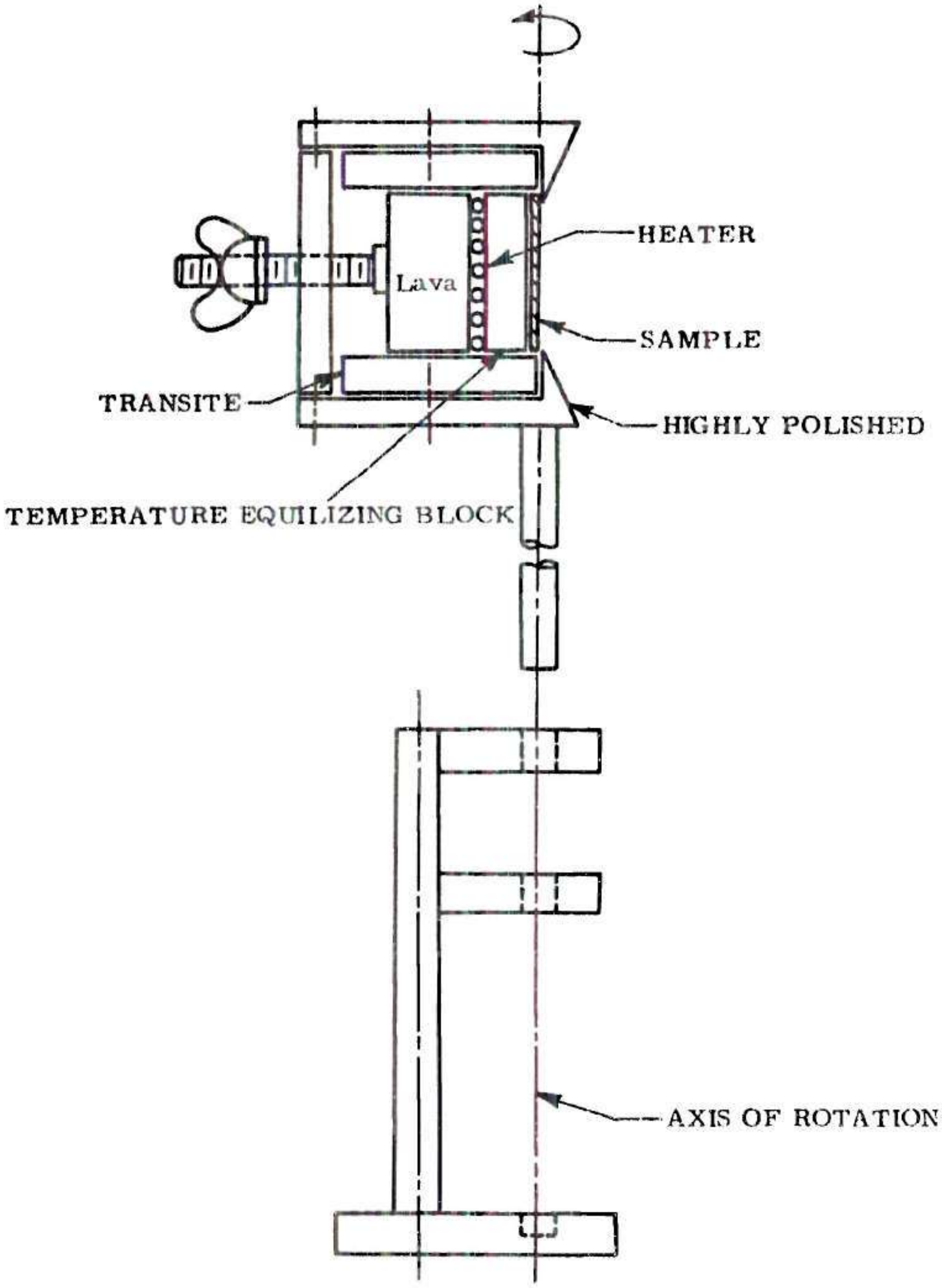
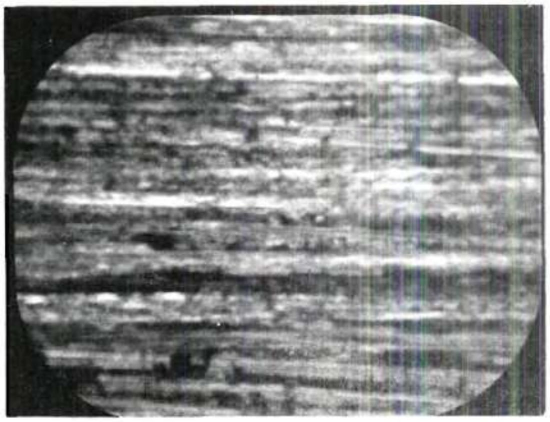
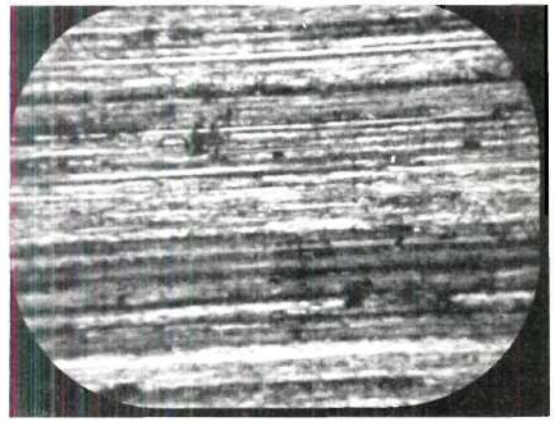


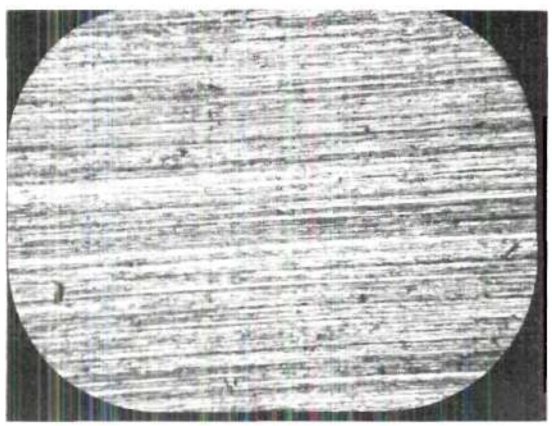
Figure 3. Sample Holder



No. 1 - 140 μin.



No. 3 - 125 μin.



No. 6 - 25 μin.

Figure 4. Photomicrograph of Roughened Aluminum Surfaces, Magnification X20

APPENDIX A

SAMPLE CALCULATION

The sample calculation will be performed using the actual test as shown on data sheet 10 in Appendix B.

Equation (16) is used in calculating the directional emissivity.

$$\epsilon_{S\theta} = \frac{T_B^4 - T_G^4}{T_S^4 - T_G^4} \times \frac{d_{S\theta} - d_G}{d_B - d_G}$$

Then inserting values found on data sheet for $\theta = 80$

$$\epsilon_{S\theta} = \frac{(598.7)^4 - (537)^4}{(787)^4 - (537)^4} \times \frac{(27.3 - 5.3)}{(35.7 - 5.3)}$$

$\theta = 80$

$$= \frac{(12.8480 - 8.3156) \times 10^{10}}{(38.3618 - 8.3156) \times 10^{10}} \times \frac{22.0}{30.4}$$

$$= \frac{4.5324}{30.0462} \times \frac{22.0}{30.4}$$

$$= 0.119$$

APPENDIX B

Copies of actual data sheets are shown on the next pages. The numbers and symbols used thereon are described below.

1. Blackbody (heated) thermocouples, front.
2. Blackbody (heated) thermocouple, middle.
3. Blackbody (heated) thermocouple, end.
4. Blackbody (heated) thermocouple, back side.
5. Copper equalizer block, thermocouple.
6. Sample surface thermocouple.
7. A guard blackbody thermocouple.
8. Water cooled surroundings of the sample holder thermocouple.
9. Water cooled surroundings of radiometer thermocouple.

$\Delta_{S\theta}$ - K-3 potentiometer reading (μv) when radiometer is sighted at sample — K-3 potentiometer reading (μv) when radiometer is sighted at blackbody guard.

ΔB - K-3 potentiometer reading (μv) when radiometer is sighted at heated blackbody — K-3 potentiometer reading (μv) when radiometer is sighted at guard blackbody.

DATA SHEET NO. 1

Sample: Pure Aluminum (99%)(Well Polished) Date: July 1, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.410	2.425	2.425	2.416	4.494	4.304	0.960	0.966	0.970

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	8.4	35.2	5	0°	3.4	30.2	.0408	1.00
5	10°	8.4	35.2	5	10°	3.4	30.2	.0408	1.00
5	20°	8.4	35.2	5	20°	3.4	30.2	.0408	1.00
5	30°	8.4	35.2	5	30°	3.4	30.2	.0408	1.00
5	40°	8.5	35.2	5	40°	3.5	30.2	.0432	1.04
5	50°	8.5	35.2	5	50°	3.5	30.2	.0432	1.04
5	60°	8.6	35.2	5	60°	3.6	30.2	.0445	1.09
5	70°	10.4	35.2	5	70°	5.4	30.2	.0665	1.62
5	75°	11.0	35.2	5	75°	6.0	30.2	.0738	1.80
5	80°	13.0	35.2	5	80°	8.0	30.2	.0988	2.42
5	82°	14.0	35.2	5	82°	9.0	30.2	.1110	2.72

T_G	76°F	536°R	T_S	213°F	673°R	T_B	138°F	598°R

DATA SHEET NO. 2

Sample: Black Painted Body (acetylene soot) Date: July 3, 1966

Apparatus: Type K-3 Universal Potentiometer
and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.258	2.350	2.245	2.234	2.303	2.210	0.970	0.950	0.960

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	63.2	66	14	0°	49.2	52	.998	1.000
5	10°	63.2	66	14	10°	49.2	52	.998	1.000
5	20°	63.2	66	14	20°	49.2	52	.998	1.000
5	30°	63.2	66	14	30°	49.2	52	.998	1.000
5	40°	63.2	66	14	40°	49.2	52	.998	1.000
5	50°	63.1	66	14	50°	49.1	52	.996	0.998
5	60°	62.9	66	14	60°	48.9	52	.992	0.994
5	70°	59.0	66	14	70°	45.0	52	.913	0.915
5	75°	56.0	66	14	75°	42.0	52	.850	0.852
5	80°	54.6	66	14	80°	40.6	52	.824	0.826
5	82°	53.5	66	14	82°	39.5	52	.802	0.803

T_G	75.2°F	535.2°R	T_S	129.4°F	589.4°R	T_B	132°F	592°R

DATA SHEET NO. 3

Sample: No. 1 Rough (140 μ in.) Date: July 10, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.386	2.450	2.450	2.500	4.494	4.290	0.952	0.938	0.948

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	9.3	35.2	1.5	0°	7.8	33.7	.0905	1.000
5	10°	9.3	35.2	1.5	10°	7.8	33.7	.0905	1.000
5	20°	9.4	35.2	1.5	20°	7.9	33.7	.0916	1.012
5	30°	9.5	35.2	1.5	30°	8.0	33.7	.0928	1.025
5	40°	9.8	35.2	1.5	40°	8.3	33.7	.0963	1.064
5	50°	10.2	35.2	1.5	50°	8.7	33.7	.1009	1.115
5	60°	10.7	35.2	1.5	60°	9.2	33.7	.1060	1.171
5	70°	11.6	35.2	1.5	70°	10.1	33.7	.1172	1.295
5	75°	12.8	35.2	1.5	75°	11.3	33.7	.1311	1.448
5	80°	13.7	35.2	1.5	80°	12.2	33.7	.1415	1.560
5	82°	14.9	35.2	1.5	82°	13.4	33.7	.1550	1.712

T_G	74.5°F	534.5°R	T_S	210.5°F	670.5°R	T_B	139°F	599°R

DATA SHEET NO. 4

Sample: No. 1 Rough (140 μ in.)   Date: July 11, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector   By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.456	2.485	2.495	2.508	7.615	7.178	0.965	0.950	0.960

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	22.6	37.2	3	0°	19.6	34.2	.0969	1.000
5	10°	22.6	37.2	3	10°	19.6	34.2	.0969	1.000
5	20°	22.9	37.2	3	20°	19.9	34.2	.0984	1.015
5	30°	23.4	37.2	3	30°	20.4	34.2	.1009	1.114
5	40°	23.9	37.2	3	40°	20.9	34.2	.1033	1.066
5	50°	24.9	37.2	3	50°	21.9	34.2	.1080	1.114
5	60°	26.1	37.2	3	60°	23.1	34.2	.1142	1.178
5	70°	29.0	37.2	3	70°	26.0	34.2	.1286	1.327
5	75°	31.95	37.2	3	75°	29.0	34.2	.1430	1.475
5	80°	34.55	37.2	3	80°	31.6	34.2	.1560	1.610
5	82°	37.1	37.2	3	82°	24.1	34.2	.1680	1.733

T_G	75.2°F	535.2°R	T_S	319°F	779°R	T_B	141°F	601°R

DATA SHEET NO. 5

Sample: No. 2 Well Polished — Date: July 12, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector — By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.388	2.422	2.37	2.365	4.490	4.286	0.950	0.940	0.956

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	9.1	34.7	4.5	0°	4.6	30.2	.0547	1.000
5	10°	9.1	34.7	4.5	10°	4.6	30.2	.0547	1.000
5	20°	9.1	34.7	4.5	20°	4.6	30.2	.0547	1.000
5	30°	9.2	34.7	4.5	30°	4.7	30.2	.0559	1.049
5	40°	9.2	34.7	4.5	40°	4.7	30.2	.0559	1.049
5	50°	9.6	34.7	4.5	50°	5.1	30.2	.0606	1.108
5	60°	9.9	34.7	4.5	60°	5.4	30.2	.0640	1.170
5	70°	10.5	34.7	4.5	70°	6.0	30.2	.0714	1.305
5	75°	11.2	34.7	4.5	75°	6.7	30.2	.0797	1.457
5	80°	13.3	34.7	4.5	80°	8.8	30.2	.1047	1.914
5	82°	17.0	34.7	4.5	82°	12.5	30.2	.1480	2.705

T_G	75°F	535°R	T_S	212.3°F	672.3°R	T_B	136.6°F	596.6°R

DATA SHEET NO. 6

Sample: No. 2 Well Polished | Date: July 15, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector | By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.456	2.457	2.436	2.420	7.815	7.300	0.980	0.950	0.960

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	13.6	36	4.6	0°	9.0	31.4	.0504	1.000
5	10°	13.6	36	4.6	10°	9.0	31.4	.0504	1.000
5	20°	13.6	36	4.6	20°	9.0	31.4	.0504	1.000
5	30°	13.7	36	4.6	30°	9.1	31.4	.0511	1.038
5	40°	14.0	36	4.6	40°	9.4	31.4	.0526	1.045
5	50°	14.9	36	4.6	50°	10.3	31.4	.0577	1.145
5	60°	15.1	36	4.6	60°	10.5	31.4	.0587	1.164
5	70°	16.4	36	4.6	70°	11.8	31.4	.0661	1.311
5	75°	19.6	36	4.6	75°	15.0	31.4	.0844	1.668
5	80°	25.0	36	4.6	80°	20.4	31.4	.1140	2.260
5	82°	32.6	36	4.6	82°	28.2	31.4	.1560	3.090

T_G	75.2°F	535.2°R	T_S	323°F	783°R	T_B	139°F	599°R

DATA SHEET NO. 7

Sample: No. 3 Rough (125 μ in.) Date: July 18, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector

By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.360	2.375	2.358	2.376	4.480	4.240	0.950	0.947	0.956

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	$\Delta\theta$	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	10.2	34.1	4.1	0°	6.1	30.0	.0748	1.000
5	10°	10.2	34.1	4.1	10°	6.1	30.0	.0748	1.000
5	20°	10.3	34.1	4.1	20°	6.2	30.0	.0760	1.016
5	30°	10.3	34.1	4.1	30°	6.2	30.0	.0760	1.016
5	40°	10.7	34.1	4.1	40°	6.6	30.0	.0809	1.081
5	50°	11.1	34.1	4.1	50°	7.0	30.0	.0858	1.147
5	60°	11.5	34.1	4.1	60°	7.4	30.0	.0907	1.212
5	70°	12.5	34.1	4.1	70°	8.4	30.0	.1030	1.377
5	75°	13.4	34.1	4.1	75°	9.4	30.0	.1150	1.537
5	80°	16.0	34.1	4.1	80°	11.9	30.0	.1460	1.952
5	82°	16.6	34.1	4.1	82°	12.5	30.0	.1530	2.045

T_G	75°F	535°R	T_S	210.6°F	670.6°R	T_B	136°F	596°R

DATA SHEET NO. 8

Sample: No. 3 Rough (125 μ in.) Date: July 19.1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.385	2.415	2.395	2.400	7.820	7.300	0.970	0.995	0.960

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	23.8	35	4.1	0°	19.7	30.9	.1050	1.000
5	10°	23.8	35	4.1	10°	19.7	30.9	.1050	1.000
5	20°	24.1	35	4.1	20°	20.0	30.9	.1069	1.018
5	30°	24.6	35	4.1	30°	20.5	30.9	.1095	1.043
5	40°	25.5	35	4.1	40°	21.4	30.9	.1140	1.085
5	50°	26.7	35	4.1	50°	22.6	30.9	.1200	1.143
5	60°	28.0	35	4.1	60°	23.9	30.9	.1278	1.217
5	70°	29.1	35	4.1	70°	25.0	30.9	.1330	1.266
5	75°	30.1	35	4.1	75°	26.0	30.9	.1380	1.314
5	80°	33.6	35	4.1	80°	29.5	30.9	.1570	1.495
5	82°	34.6	35	4.1	82°	30.5	30.9	.1630	1.552

T_G	75.4°F	535.4°R	T_S	323.2°F	783.2°R	T_B	137°F	597°R

DATA SHEET NO. 9

Sample: No. 5 Well Polished | Date: July 20, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector | By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.365	2.358	2.356	2.375	4.484	4.240	0.975	0.968	0.970

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	9.5	35.0	5.0	0°	4.5	30.0	.0546	1.000
5	10°	9.5	35.0	5.0	10°	4.5	30.0	.0546	1.000
5	20°	9.5	35.0	5.0	20°	4.5	30.0	.0546	1.000
5	30°	9.5	35.0	5.0	30°	4.5	30.0	.0546	1.000
5	40°	10.0	35.0	5.0	40°	5.0	30.0	.0607	1.112
5	50°	10.2	35.0	5.0	50°	5.2	30.0	.0632	1.160
5	60°	10.5	35.0	5.0	60°	5.5	30.0	.0668	1.223
5	70°	11.8	35.0	5.0	70°	6.8	30.0	.0826	1.513
5	75°	12.0	35.0	5.0	75°	7.0	30.0	.0850	1.556
5	80°	14.1	35.0	5.0	80°	9.1	30.0	.1100	2.014
5	82°	16.7	35.0	5.0	82°	11.7	30.0	.1420	2.600

T_G	76°F	536°R	T_S	210.6°F	670.6°R	T_B	136°F	596°R

DATA SHEET NO. 10

Sample: No. 5 Well Polished — Date: July 21, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector — By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.442	2.467	2.430	2.400	7.980	7.410	1.003	0.990	0.996

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	15.6	35.7	5.3	0°	10.3	30.4	.0511	1.000
5	10°	15.6	35.7	5.3	10°	10.3	30.4	.0511	1.000
5	20°	15.6	35.7	5.3	20°	10.3	30.4	.0511	1.000
5	30°	15.6	35.7	5.3	30°	10.3	30.4	.0511	1.000
5	40°	17.0	35.7	5.3	40°	11.7	30.4	.0580	1.135
5	50°	17.3	35.7	5.3	50°	12.0	30.4	.0595	1.164
5	60°	17.6	35.7	5.3	60°	12.3	30.4	.0610	1.194
5	70°	19.5	35.7	5.3	70°	14.2	30.4	.0704	1.378
5	75°	22.5	35.7	5.3	75°	17.2	30.4	.0853	1.669
5	80°	27.3	35.7	5.3	80°	22.0	30.4	.1190	2.133
5	82°	33.3	35.7	5.3	82°	29.0	30.4	.1430	2.798

T_G	77°F	537°R	T_S	327°F	787°R	T_B	138.7°F	598.7°R

DATA SHEET NO. 11

Sample: No. 6 Rough (25 μ in.) Date: July 23, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.345	2.396	2.357	2.358	7.720	7.260	0.950	0.946	0.942

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	20.4	34	4	0°	16.4	30	.0830	1.000
5	10°	21.1	34	4	10°	17.1	30	.0860	1.036
5	20°	21.2	34	4	20°	17.2	30	.0868	1.040
5	30°	21.5	34	4	30°	17.5	30	.0884	1.065
5	40°	21.8	34	4	40°	17.8	30	.0899	1.083
5	50°	23.6	34	4	50°	19.6	30	.0990	1.193
5	60°	24.1	34	4	60°	20.1	30	.1015	1.223
5	70°	26.4	34	4	70°	22.4	30	.1131	1.362
5	75°	30.6	34	4	75°	26.6	30	.1340	1.615
5	80°	35.0	34	4	80°	31.0	30	.1560	1.879
5	82°	37.0	34	4	82°	33.0	30	.1660	2.000

T_G	75°F	535°R	T_S	322°F	782°R	T_B	136°F	596°R

DATA SHEET NO. 12

Sample: No. 6 Rough (25 μ in.) Date: July 23, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.438	2.463	2.425	2.400	4.520	4.348	0.982	0.970	0.976

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	10.1	34.5	4.0	0°	6.1	30.5	.0738	1.000
5	10°	10.1	34.5	4.0	10°	6.1	30.5	.0738	1.000
5	20°	10.1	34.5	4.0	20°	6.1	30.5	.0738	1.000
5	30°	10.2	34.5	4.0	30°	6.2	30.5	.0750	1.016
5	40°	10.4	34.5	4.0	40°	6.4	30.5	.0775	1.050
5	50°	10.8	34.5	4.0	50°	6.8	30.5	.0823	1.115
5	60°	10.9	34.5	4.0	60°	6.9	30.5	.0835	1.131
5	70°	11.9	34.5	4.0	70°	7.9	30.5	.0956	1.293
5	75°	13.3	34.5	4.0	75°	9.3	30.5	.1120	1.518
5	80°	15.9	34.5	4.0	80°	11.9	30.5	.1440	1.951
5	82°	17.5	34.5	4.0	82°	13.5	30.5	.1630	2.209

T_G	76°F	536°R	T_S	215°F	675°R	T_B	139°F	599°R

DATA SHEET NO. 13

Sample: No. 1 Rough (140 μ in.) Coated with Evaporated Al film (0.2μ)

Date: July 26, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector

By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.400	2.405	2.385	2.380	4.484	4.295	0.970	0.950	0.966

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	11.5	34.1	4.1	0°	7.4	30	.0902	1.000
5	10°	11.5	34.1	4.1	10°	7.4	30	.0902	1.000
5	20°	11.6	34.1	4.1	20°	7.5	30	.0915	1.014
5	30°	12.0	34.1	4.1	30°	7.5	30	.0915	1.014
5	40°	12.4	34.1	4.1	40°	7.9	30	.0964	1.068
5	50°	12.9	34.1	4.1	50°	8.9	30	.1010	1.119
5	60°	12.9	34.1	4.1	60°	8.9	30	.1070	1.186
5	70°	14.0	34.1	4.1	70°	9.9	30	.1200	1.219
5	75°	15.5	34.1	4.1	75°	11.4	30	.1390	1.540
5	80°	17.0	34.1	4.1	80°	12.9	30	.1570	1.740
5	82°	17.3	34.1	4.1	82°	13.2	30	.1610	1.780

T_G	75°F	535°R	T_S	213°F	673°R	T_B	137°F	597°R

DATA SHEET NO. 14

Sample: No. 1 Rough (140 μ in.) Coated with Evaporated Al film (0. 2μ)
Date: July 27, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector
By: Bapat, S. G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2. 380	2. 407	2. 390	2. 400	7. 855	7. 430	0. 980	0. 945	0. 958

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	23. 6	34. 6	3. 7	0°	19. 9	30. 1	. 0982	1. 000
5	10°	23. 8	34. 8	3. 7	10°	19. 9	30. 1	. 0982	1. 000
5	20°	24. 1	34. 8	3. 7	20°	20. 7	30. 1	. 1020	1. 038
5	30°	24. 6	34. 8	3. 7	30°	20. 9	30. 1	. 1030	1. 048
5	40°	25. 4	34. 8	3. 7	40°	21. 7	30. 1	. 1070	1. 089
5	50°	26. 4	34. 8	3. 7	50°	22. 7	30. 1	. 1120	1. 145
5	60°	27. 9	34. 8	3. 7	60°	24. 2	30. 1	. 1190	1. 212
5	70°	30. 5	34. 8	3. 7	70°	26. 8	30. 1	. 1320	1. 344
5	75°	33. 7	34. 8	3. 7	75°	30. 0	30. 1	. 1480	1. 507
5	80°	36. 7	34. 8	3. 7	80°	33. 0	30. 1	. 1620	1. 649
5	82°	38. 2	34. 8	3. 7	82°	34. 5	30. 1	. 1700	1. 731

T_G	75°F	535°R	T_S	328°F	788°R	T_B	137°F	597°R

DATA SHEET NO. 15

Sample: No. 2 Well Polished Coated with Evaporated Al film (0.2μ)

Date: July 28, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector

By: Bapat, S. G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.395	2.412	2.400	2.406	7.685	7.198	0.995	0.996	0.986

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	13.6	34.5	4.5	0°	8.6	30.0	.0443	1.000
5	10°	13.6	34.5	4.5	10°	8.6	30.0	.0443	1.000
5	20°	13.6	34.5	4.5	20°	8.6	30.0	.0443	1.000
5	30°	13.7	34.5	4.5	30°	8.7	30.0	.0447	1.039
5	40°	13.8	34.5	4.5	40°	8.8	30.0	.0452	1.051
5	50°	15.5	34.5	4.5	50°	10.5	30.0	.0540	1.256
5	60°	17.6	34.5	4.5	60°	12.6	30.0	.0648	1.507
5	70°	20.9	34.5	4.5	70°	15.9	30.0	.0815	1.895
5	75°	24.6	34.5	4.5	75°	19.6	30.0	.1008	2.340
5	80°	31.9	34.5	4.5	80°	26.9	30.0	.1378	3.200
5	82°	38.0	34.5	4.5	82°	33.0	30.0	.1690	3.930

T_G	76.5°F	536.5°R	T_S	320°F	780°R	T_B	137°F	597°R

DATA SHEET NO. 16

Sample: No. 2 Well Polished Coated with Evaporated Al film (0. 2μ)

Date: July 29, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector

By: Bapat, S. G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2. 460	2. 490	2. 470	2. 500	4. 394	4. 187	0. 990	0. 987	0. 986

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	Δ B	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	9. 3	36. 5	5. 1	0°	4. 2	31. 4	. 0518	1. 000
5	10°	9. 3	36. 5	5. 1	10°	4. 2	31. 4	. 0518	1. 000
5	20°	9. 3	36. 5	5. 1	20°	4. 2	31. 4	. 0518	1. 000
5	30°	9. 3	36. 5	5. 1	30°	4. 2	31. 4	. 0518	1. 000
5	40°	9. 6	36. 5	5. 1	40°	4. 5	31. 4	. 0555	1. 071
5	50°	10. 7	36. 5	5. 1	50°	5. 6	31. 4	. 0690	1. 332
5	60°	12. 0	36. 5	5. 1	60°	5. 9	31. 4	. 0728	1. 405
5	70°	12. 0	36. 5	5. 1	70°	6. 9	31. 4	. 0851	1. 643
5	75°	13. 6	36. 5	5. 1	75°	8. 5	31. 4	. 1050	2. 027
5	80°	16. 3	36. 5	5. 1	80°	11. 3	31. 4	. 1390	2. 680
5	82°	17. 9	36. 5	5. 1	82°	12. 7	31. 4	. 1560	3. 010

T_G	77°F	537°R	T_S	208. 5°F	668.5°R	T_B	138.5°R	598.5°R

DATA SHEET NO. 17

Sample: No. 3 Rough (125 μ in.) Coated with Evaporated Al film (0.2 μ)

Date: August 1, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector

By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.36	2.379	2.344	2.310	7.620	7.180	0.970	0.945	0.950

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	24.5	34.9	4.9	0°	19.6	30.0	.0990	1.000
5	10°	24.5	34.9	4.9	10°	19.6	30.0	.0990	1.000
5	20°	24.9	34.9	4.9	20°	20.0	30.0	.1010	1.020
5	30°	25.0	34.9	4.9	30°	20.1	30.0	.1015	1.025
5	40°	26.9	34.9	4.9	40°	22.0	30.0	.1110	1.121
5	50°	27.9	34.9	4.9	50°	23.0	30.0	.1160	1.172
5	60°	28.8	34.9	4.9	60°	23.9	30.0	.1200	1.212
5	70°	30.4	34.9	4.9	70°	25.5	30.0	.1290	1.303
5	75°	31.9	34.9	4.9	75°	27.0	30.0	.1360	1.373
5	80°	35.9	34.9	4.0	80°	31.0	30.0	.1560	1.575
5	82°	38.4	34.9	4.0	82°	33.5	30.0	.1690	1.757

T_G	75°F	535°R	T_S	319°F	779°R	T_B	135°F	595°R

DATA SHEET NO. 18

Sample: No. 3 (125 μ in.) Coated with Evaporated Al film (0.2μ) Date: August 3, 1966

Apparatus: Type K-3 Universal Potentiometer and D-C Null-detector By: Bapat, S.G.

Thermocouple Reading (mv)								
1	2	3	4	5	6	7	8	9
2.370	2.406	2.385	2.400	4.512	4.320	0.958	0.942	0.950

Time (min)	Angle	K-3 Reading (μv) Sample	Bl. Body	Guard	Angle	ΔS_θ	ΔB	ϵ_θ	$\frac{\epsilon_\theta}{\epsilon_n}$
5	0°	9.2	33.5	3.7	0°	6.0	29.8	.0745	1.000
5	10°	9.7	33.5	3.7	10°	6.0	29.8	.0745	1.000
5	20°	9.8	33.5	3.7	20°	6.1	29.8	.0757	1.016
5	30°	9.8	33.5	3.7	30°	6.1	29.8	.0757	1.016
5	40°	10.2	33.5	3.7	40°	6.5	29.8	.0807	1.083
5	50°	10.6	33.5	3.7	50°	6.9	29.8	.0856	1.149
5	60°	11.0	33.5	3.7	60°	7.3	29.8	.0906	1.215
5	70°	11.6	33.5	3.7	70°	7.9	29.8	.0980	1.315
5	75°	12.5	33.5	3.7	75°	8.8	29.8	.1090	1.463
5	80°	14.3	33.5	3.7	80°	11.6	29.8	.1440	1.933
5	82°	16.2	33.5	3.7	82°	12.5	29.8	.1550	2.080

T_G	75°F	535°R	T_S	210°F	670°R	T_B	136°F	596°R

APPENDIX C

DIRECTIONAL EMITTANCE OF VARIOUS SAMPLES

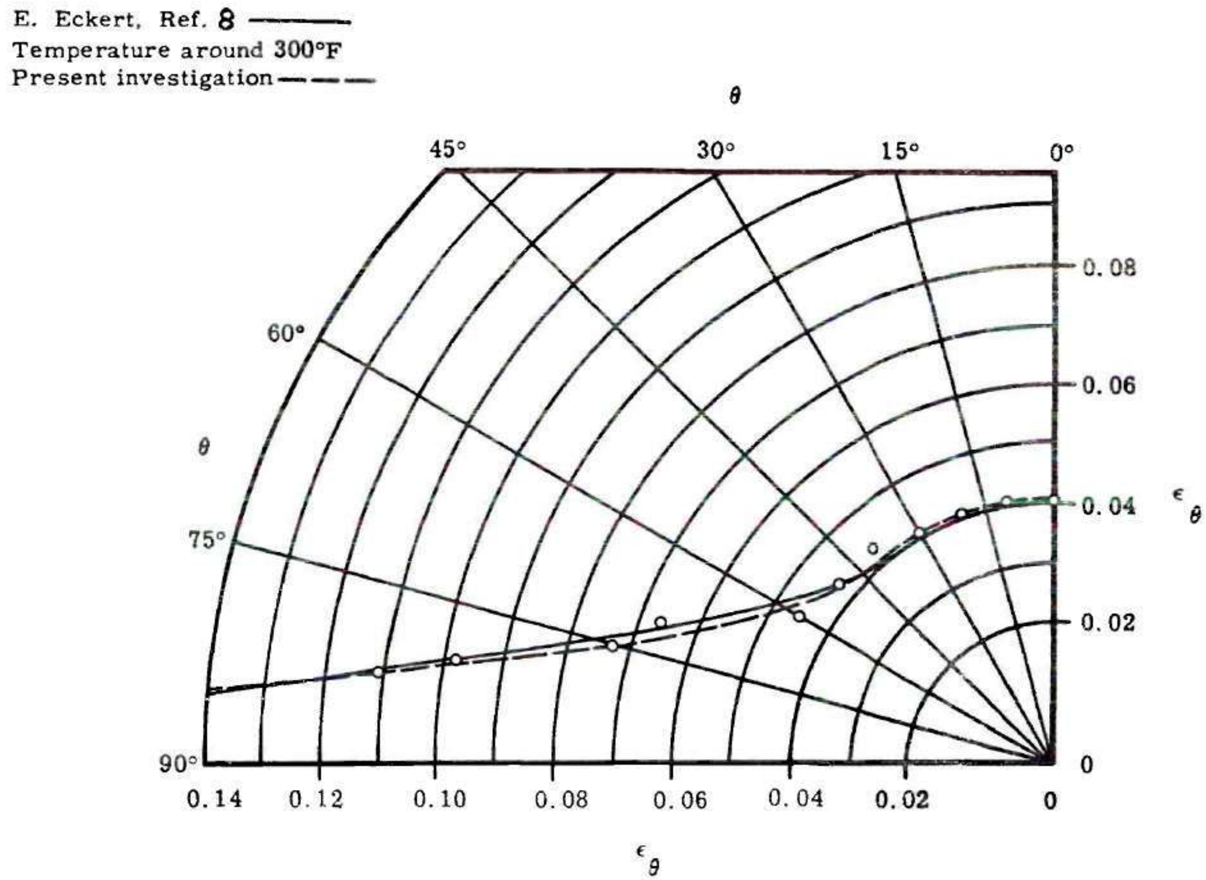


Figure 5. Aluminum Sample (99% Pure, Well Polished, 213°F)
(Total Directional Emittance)

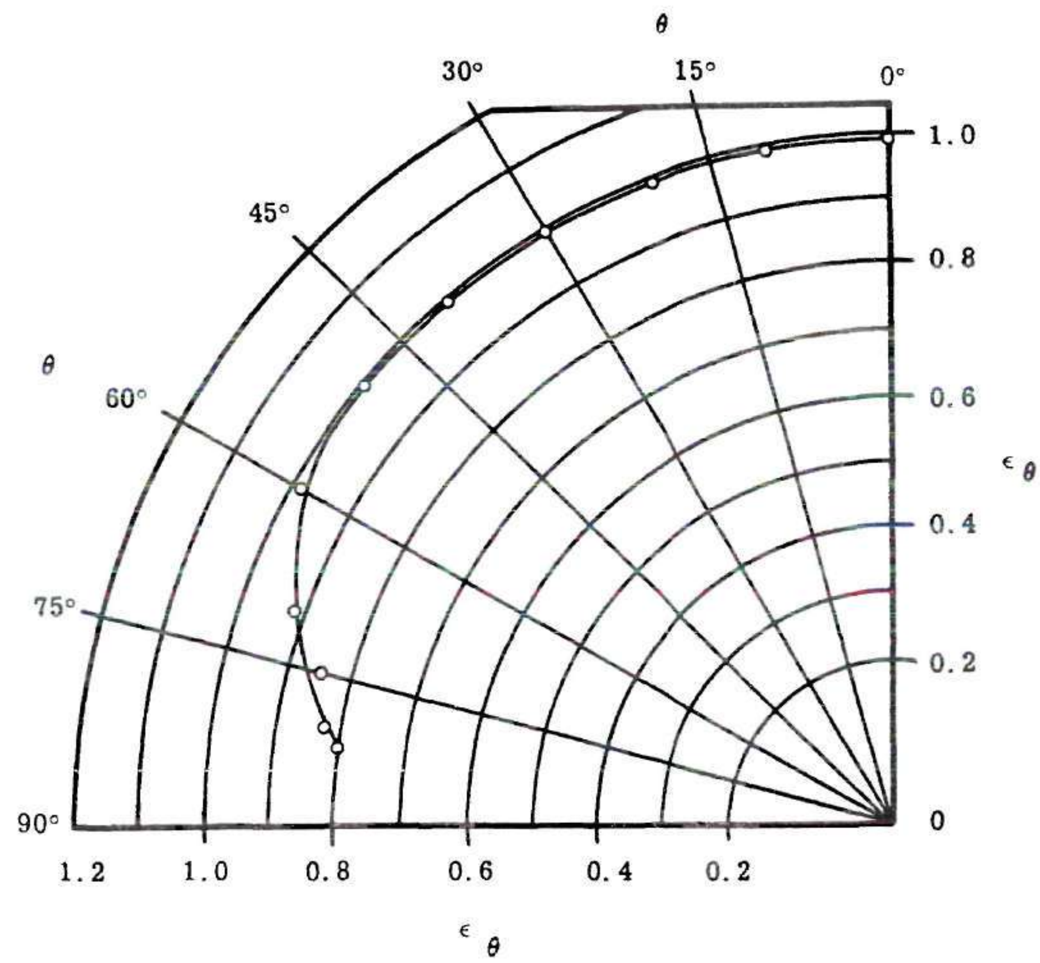


Figure 3. Black Painted Body (Total Directional Emittance)

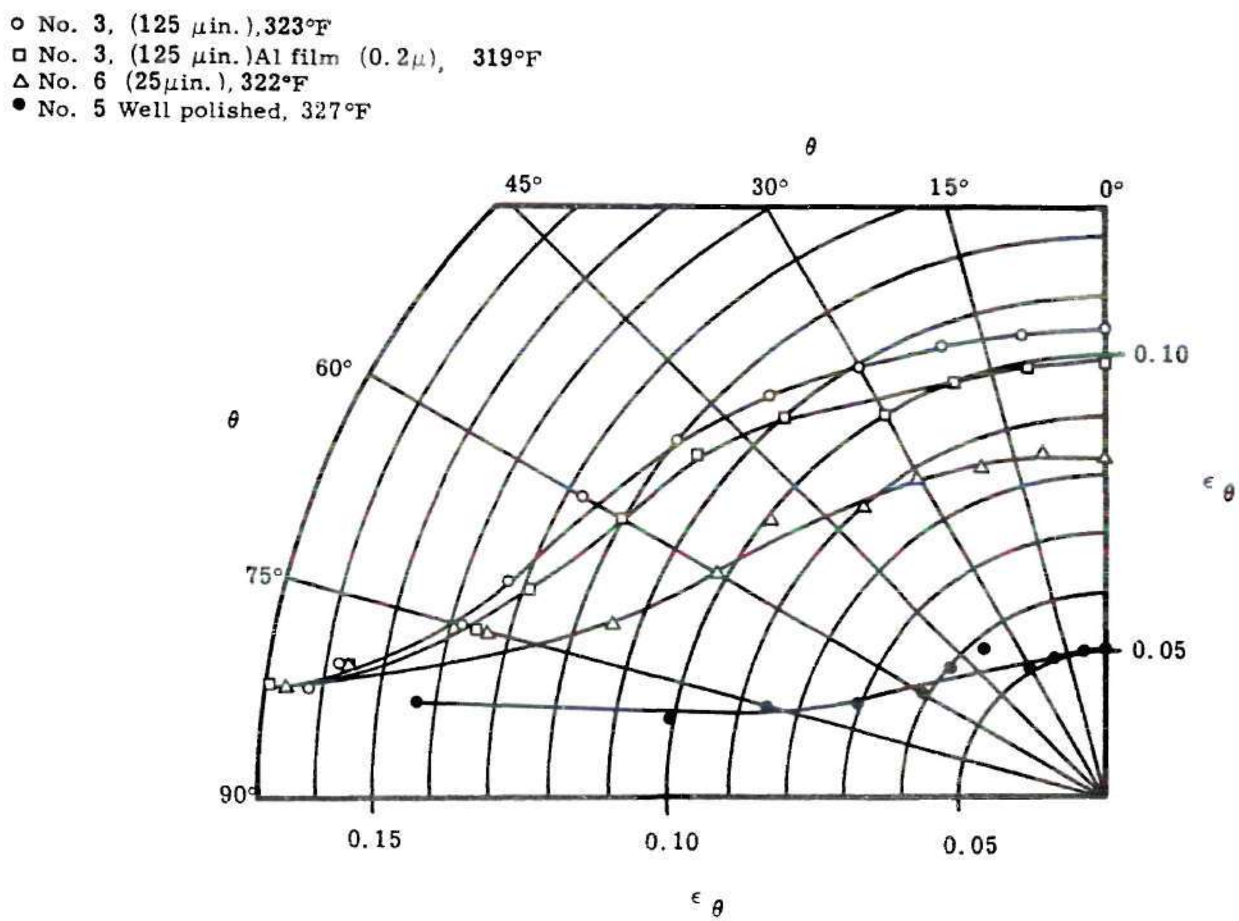


Figure 7. Test Samples (Total Directional Emittance)

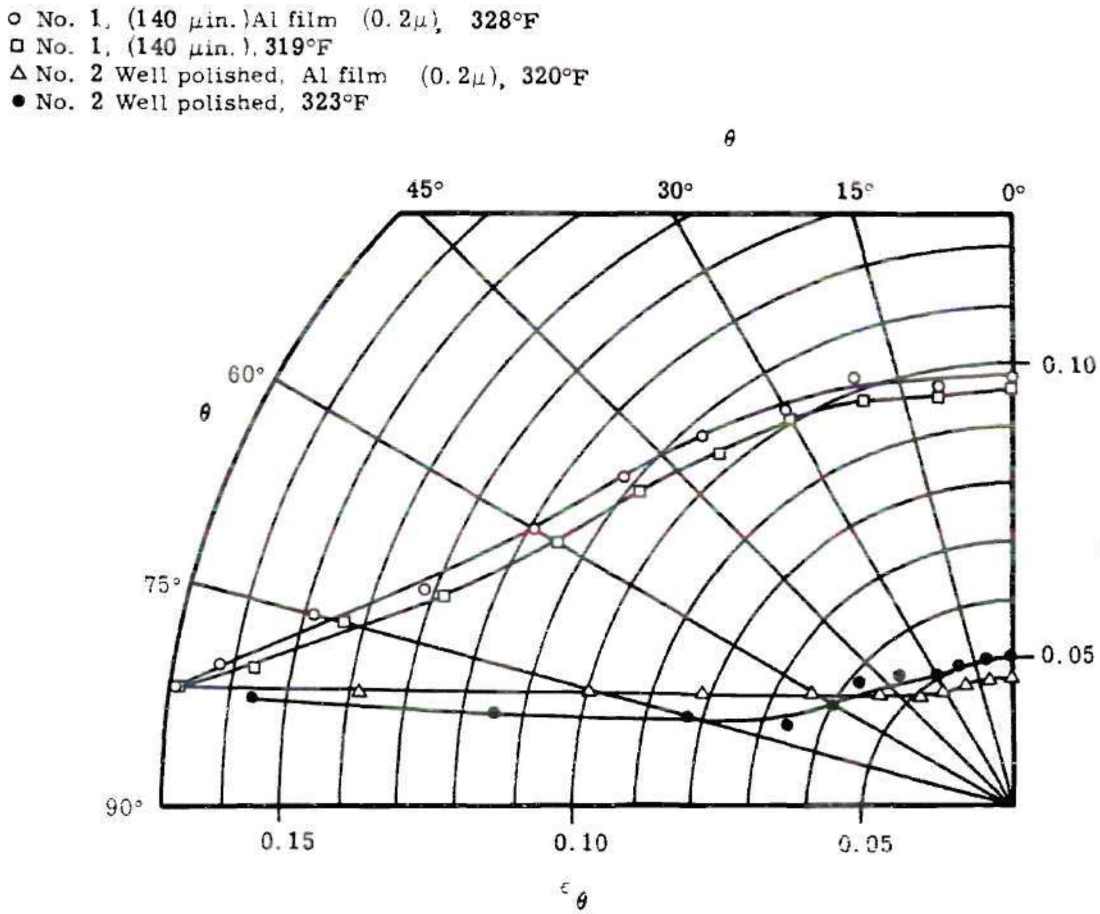


Figure 8. Test Samples (Total Directional Emittance)

o No. 3, (125 μin.), 210°F
Δ No. 3, (125 μin.), Al film (0.2μ), 210°F
□ No. 6 (25 μin.), 215°F
● No. 5 Well polished, 210°F

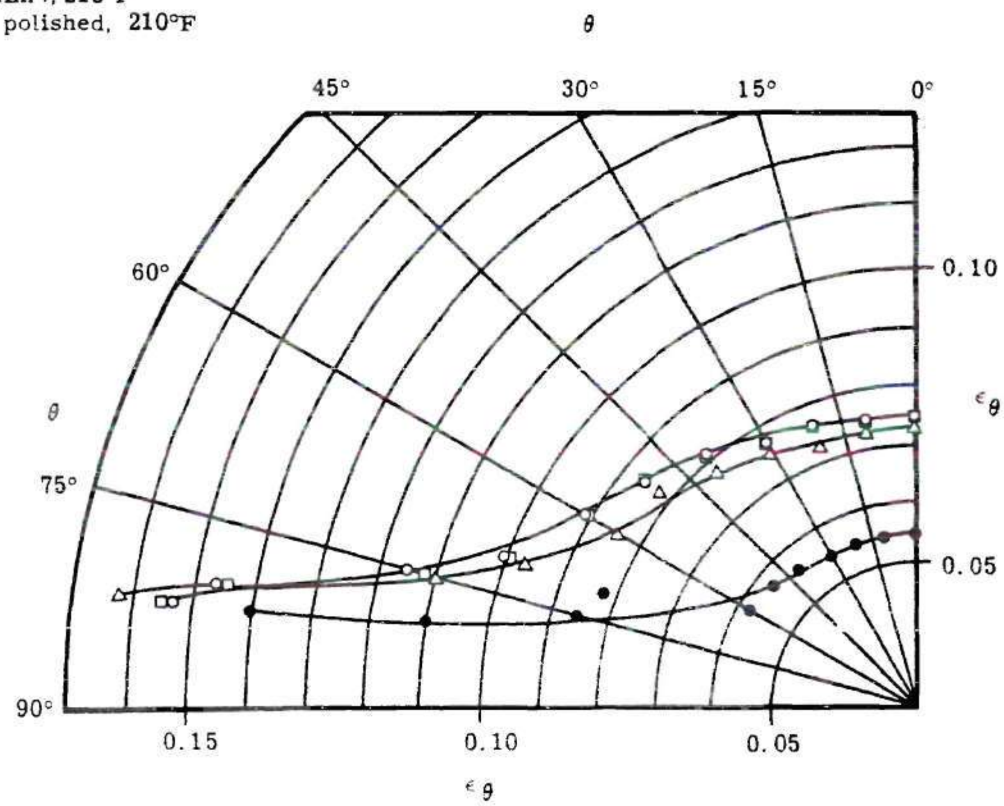


Figure 9. Test Samples (Total Directional Emittance)

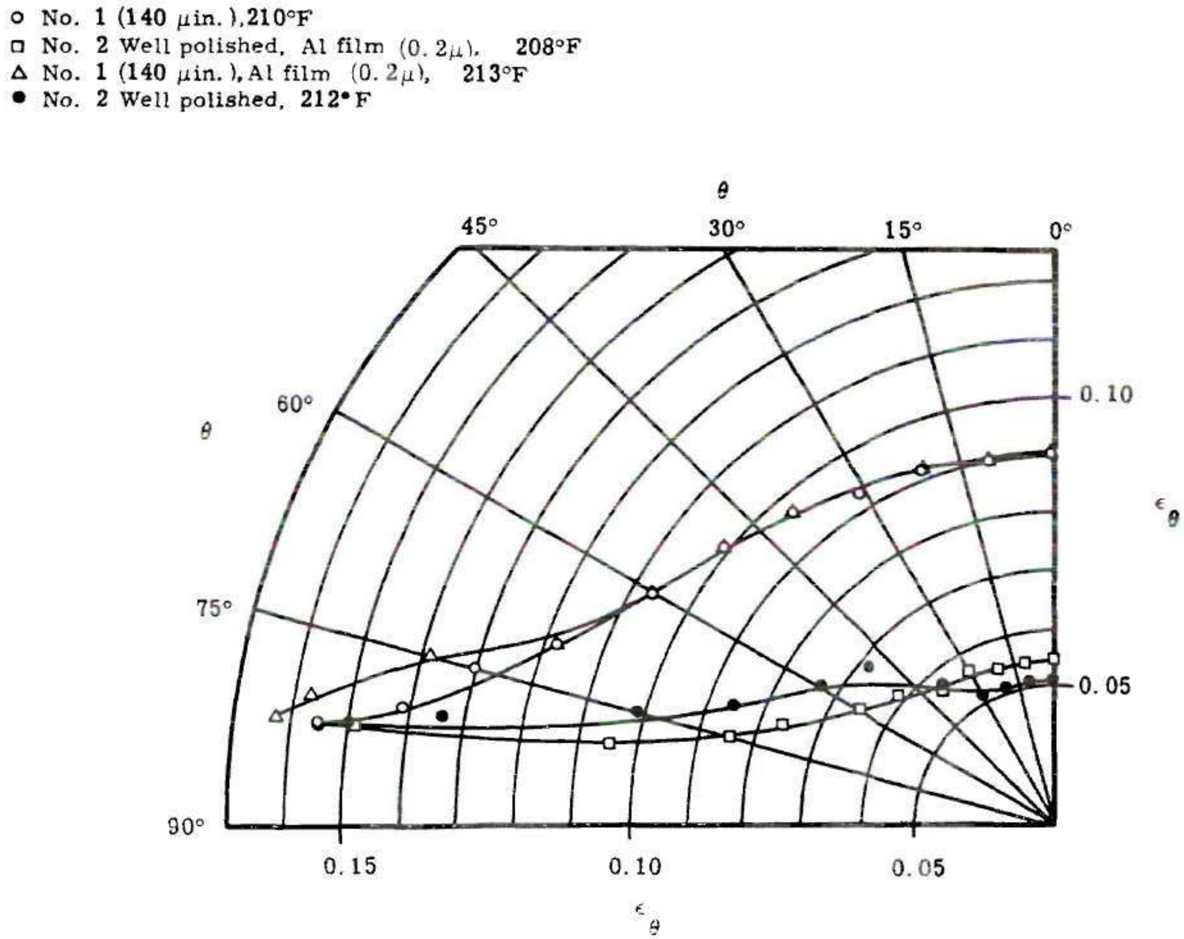


Figure 10. Test Samples (Total Directional Emittance)

APPENDIX D

RELATIVE DIRECTIONAL EMITTANCE OF VARIOUS SAMPLES

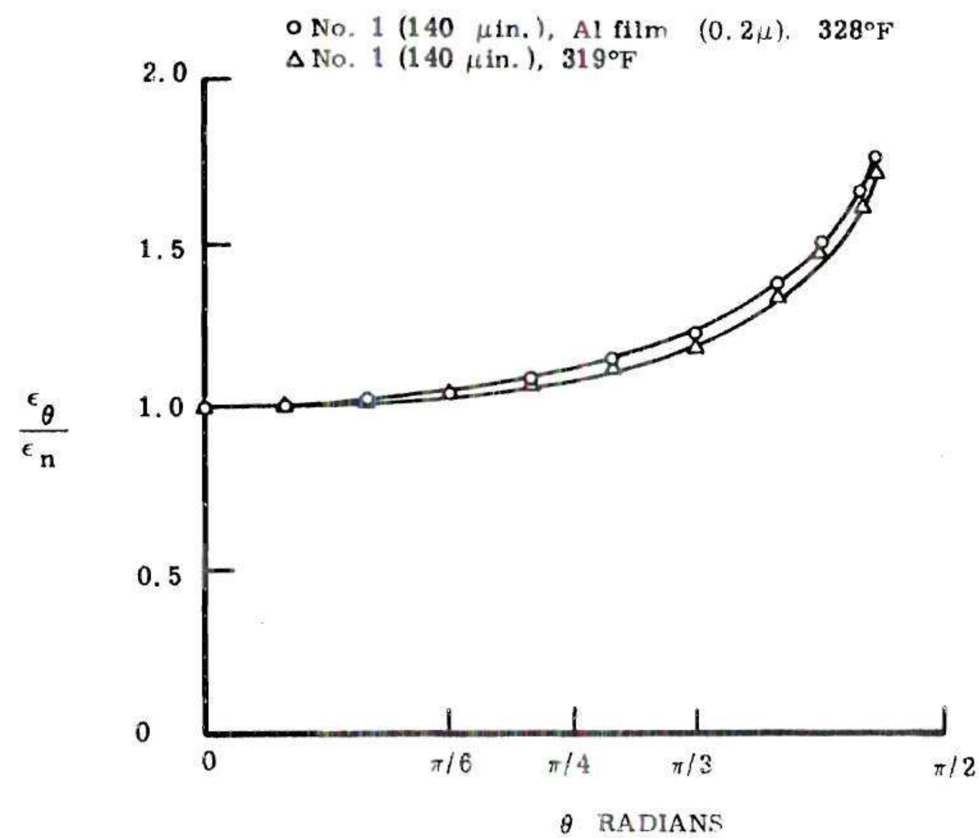


Figure 11. Test Samples (Relative Directional Emittance)

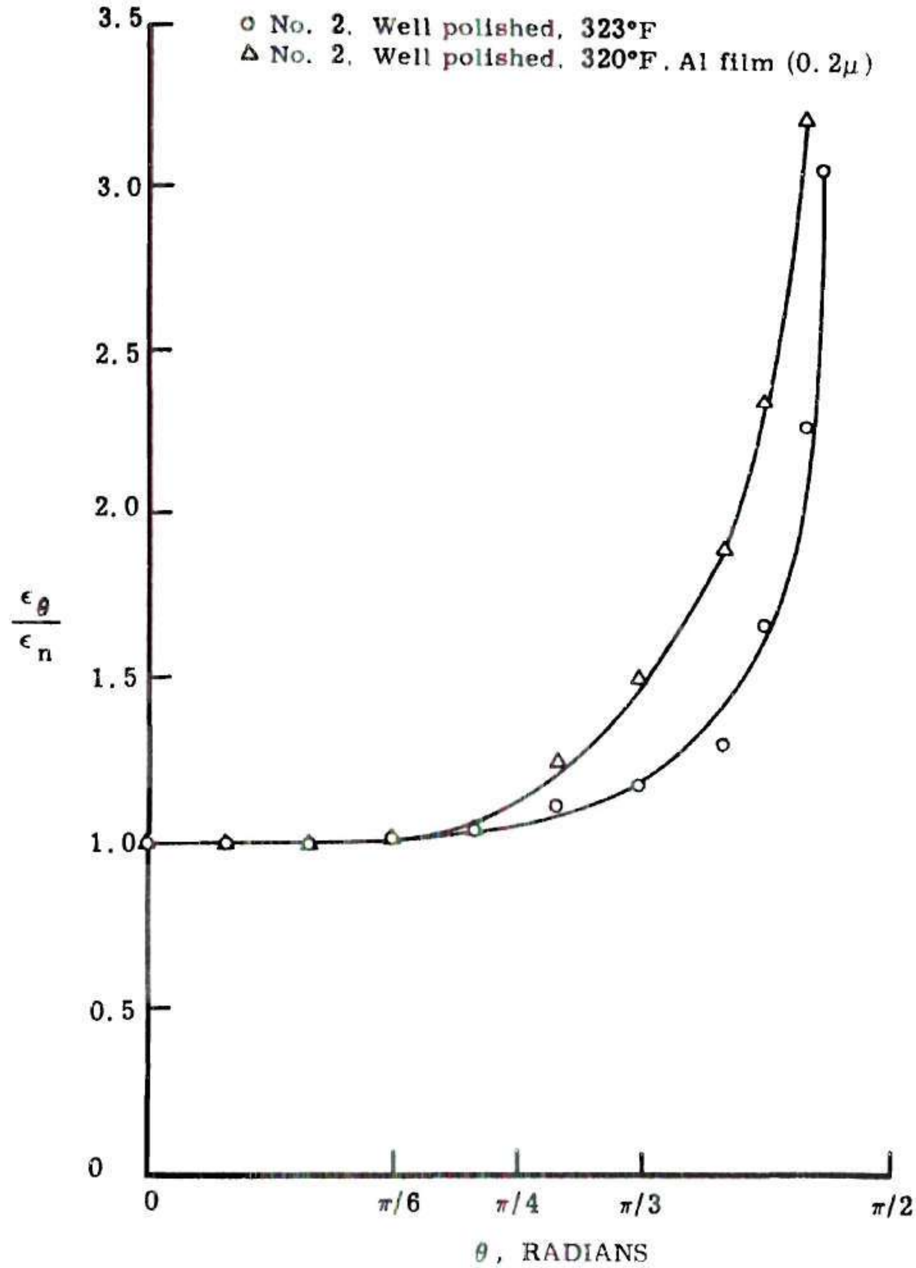


Figure 12. Test Samples (Relative Directional Emittance)

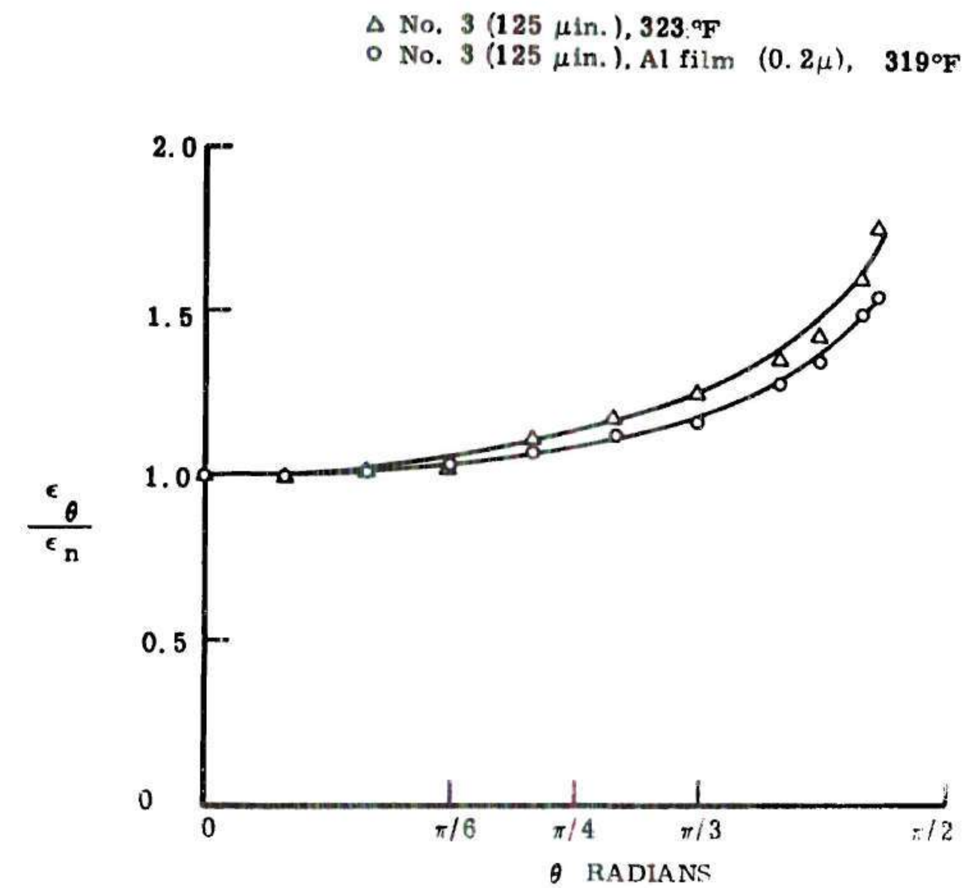


Figure 13. Test Samples (Relative Directional Emittance)

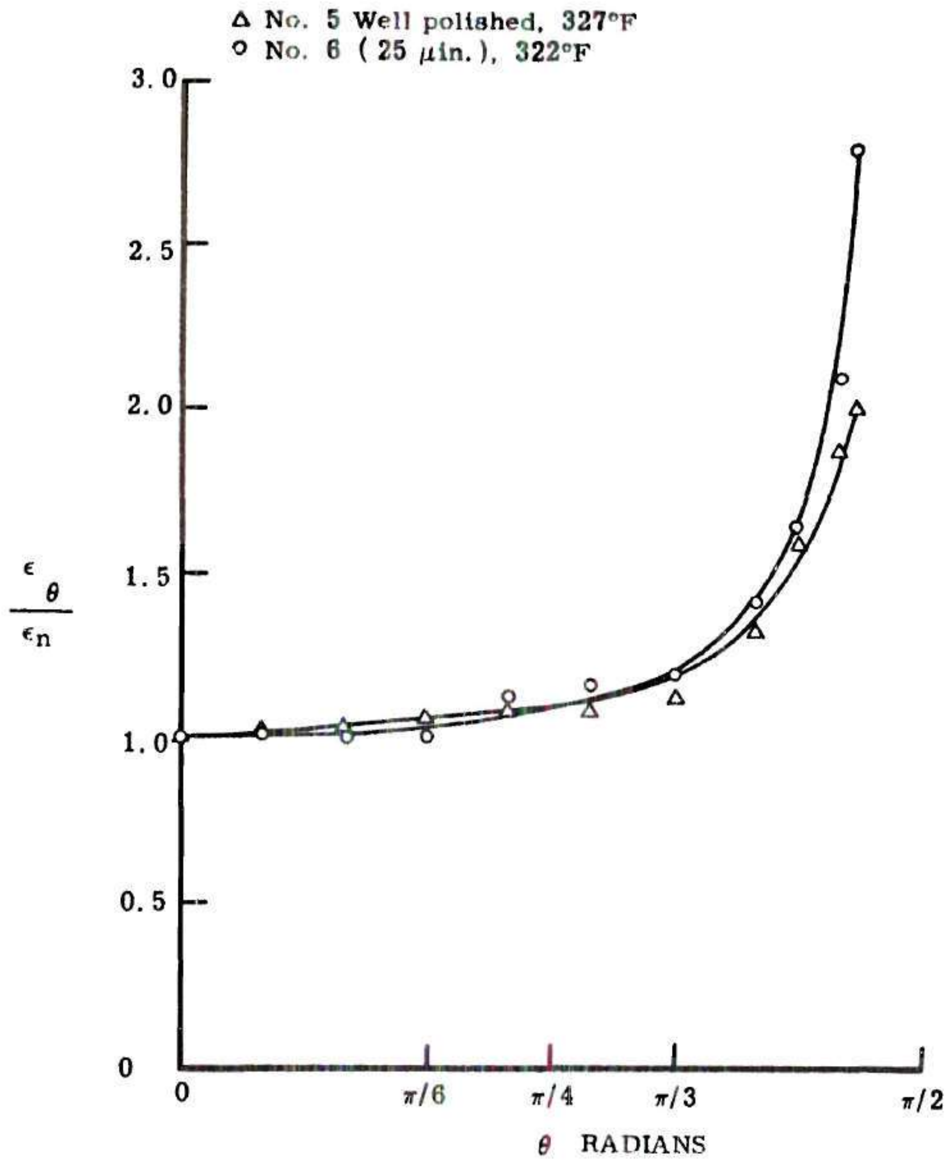


Figure 14. Test Samples (Relative Directional Emittance)

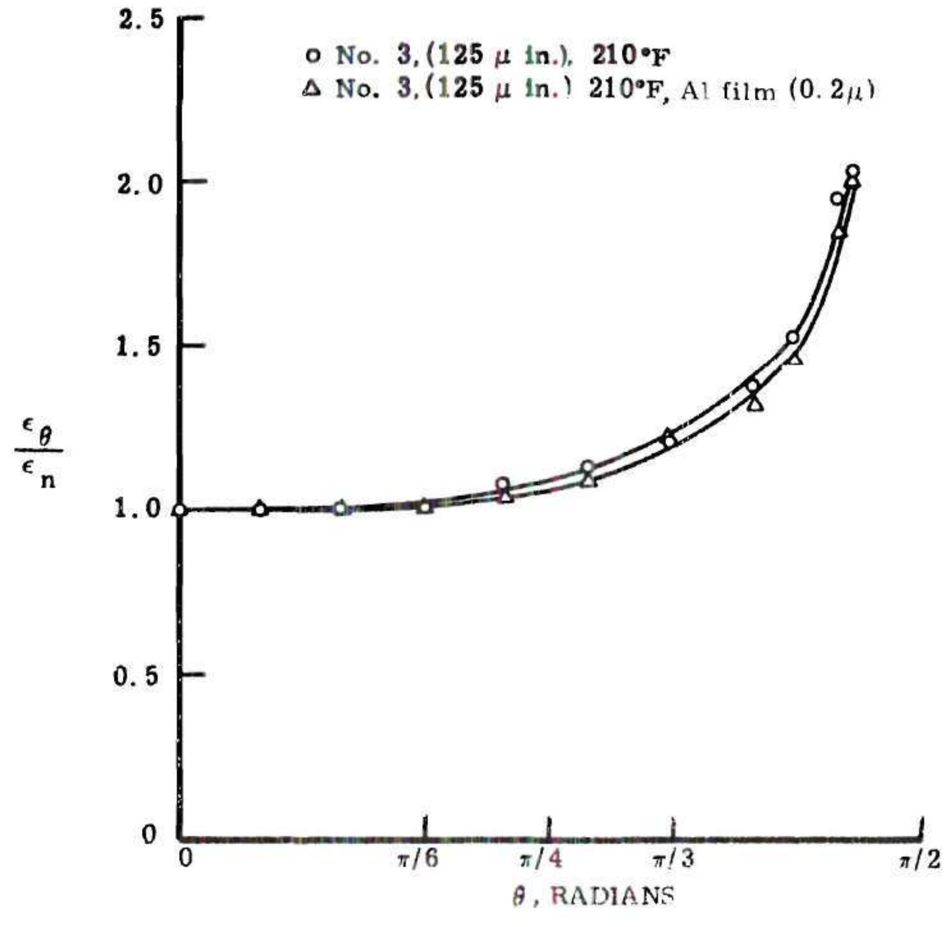


Figure 15. Test Samples (Relative Directional Emittance)

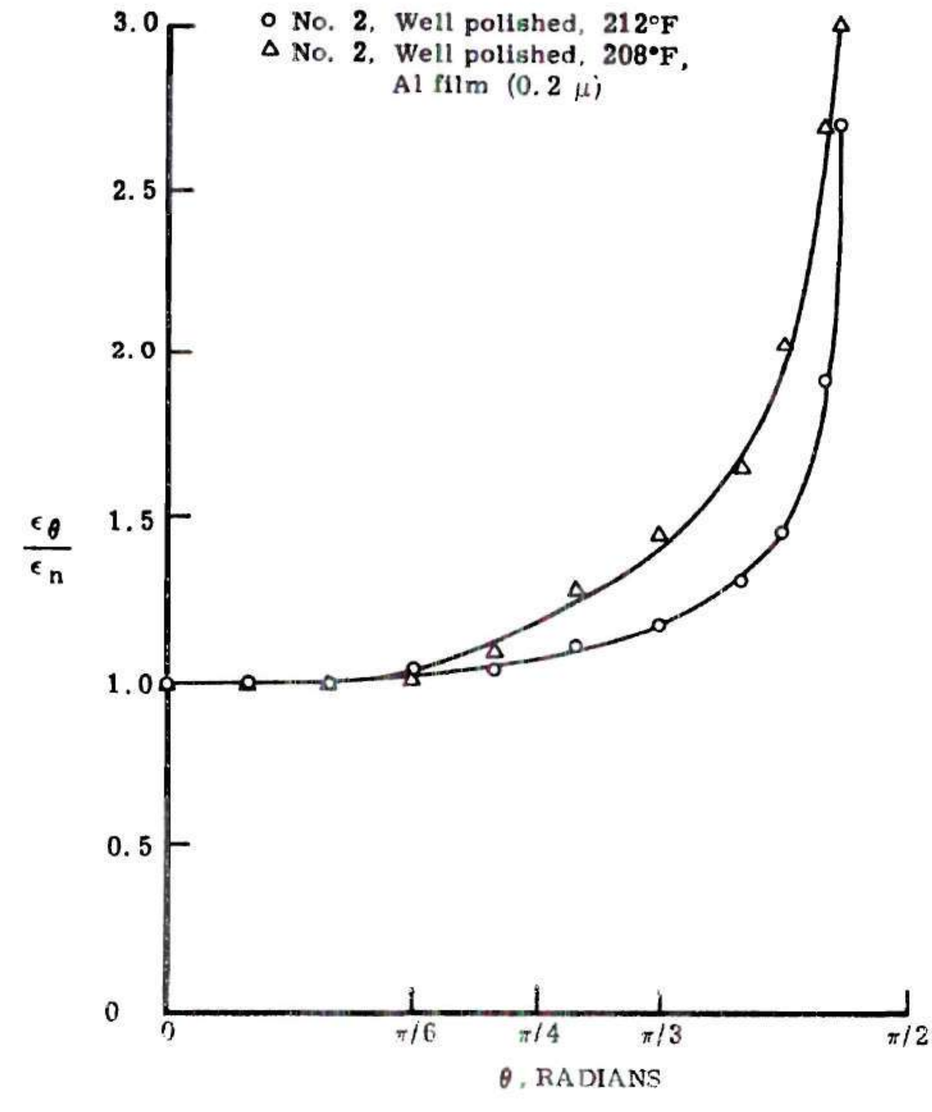


Figure 16. Test Samples (Relative Directional Emittance)

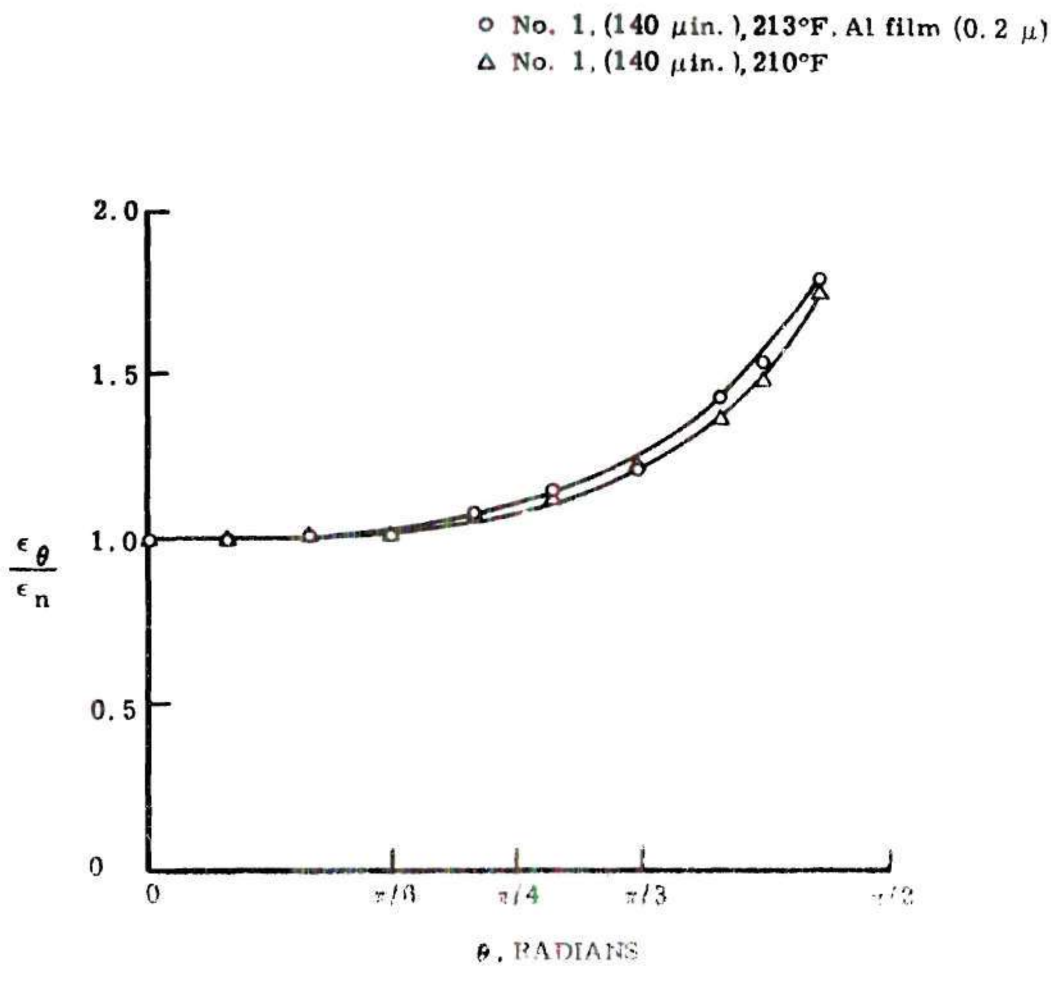


Figure 17 Test Samples (Relative Directional Emittance)

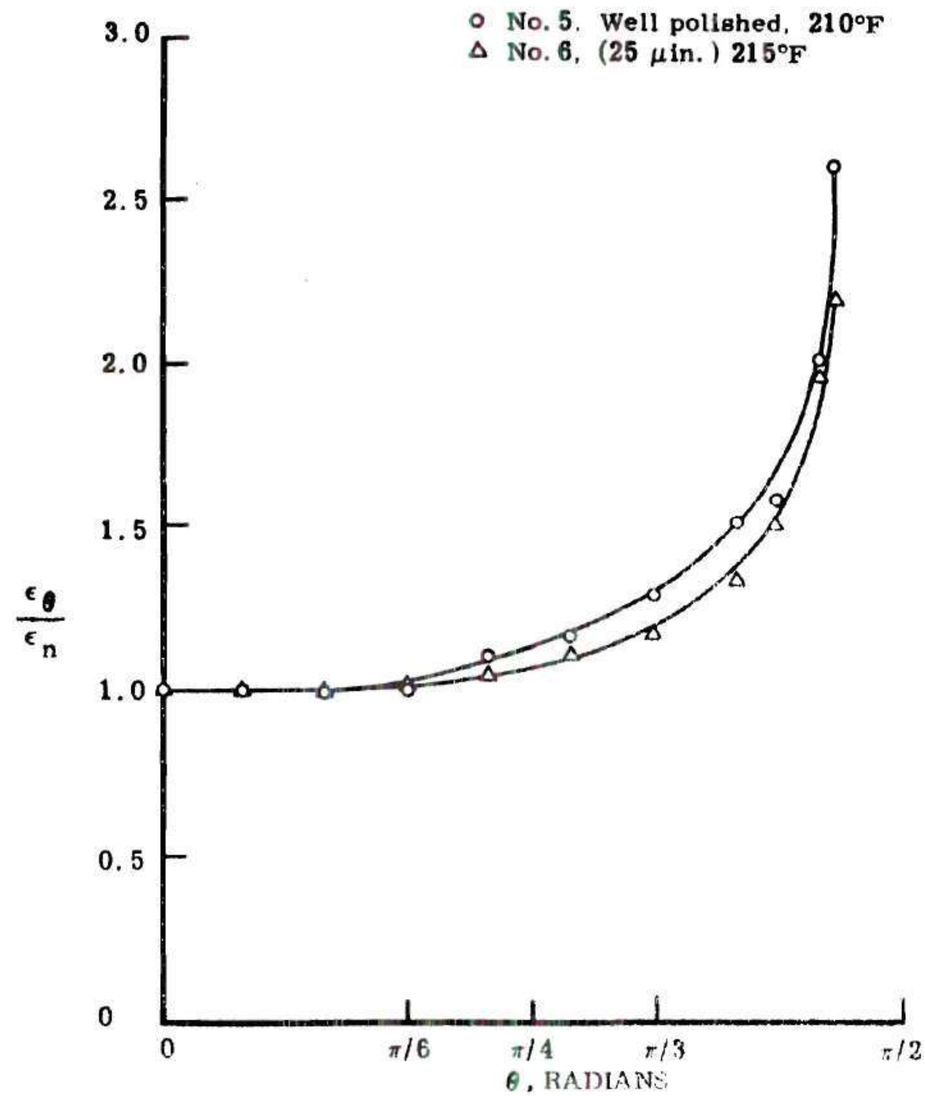


Figure 18. Test Samples (Relative Directional Emittance)

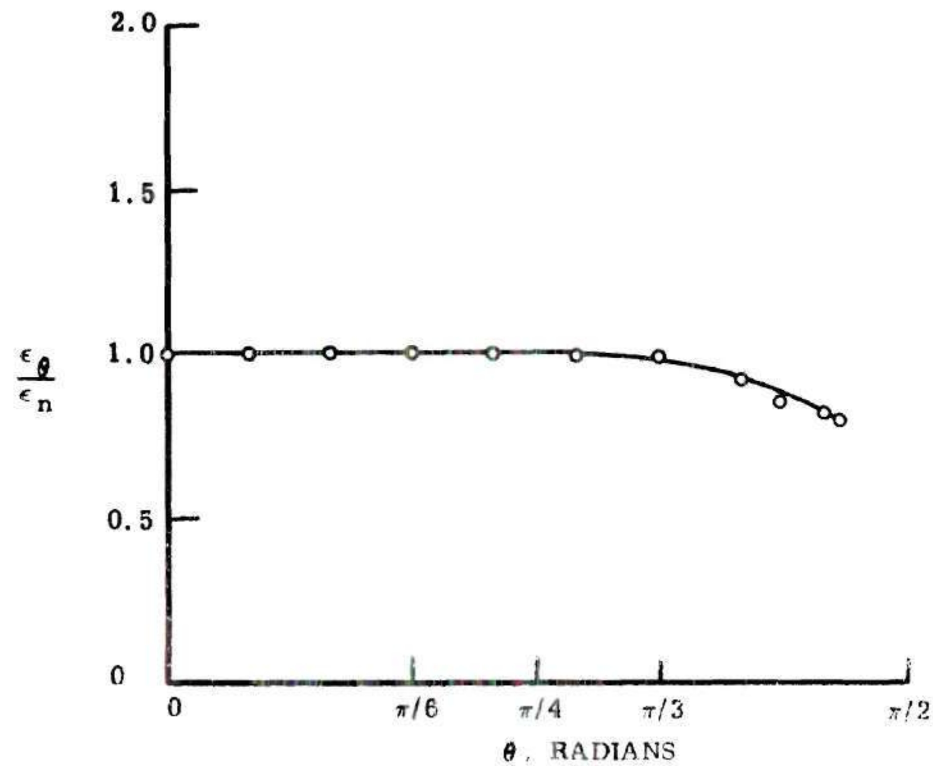


Figure 19. Black Painted Body (Relative Directional Emittance)

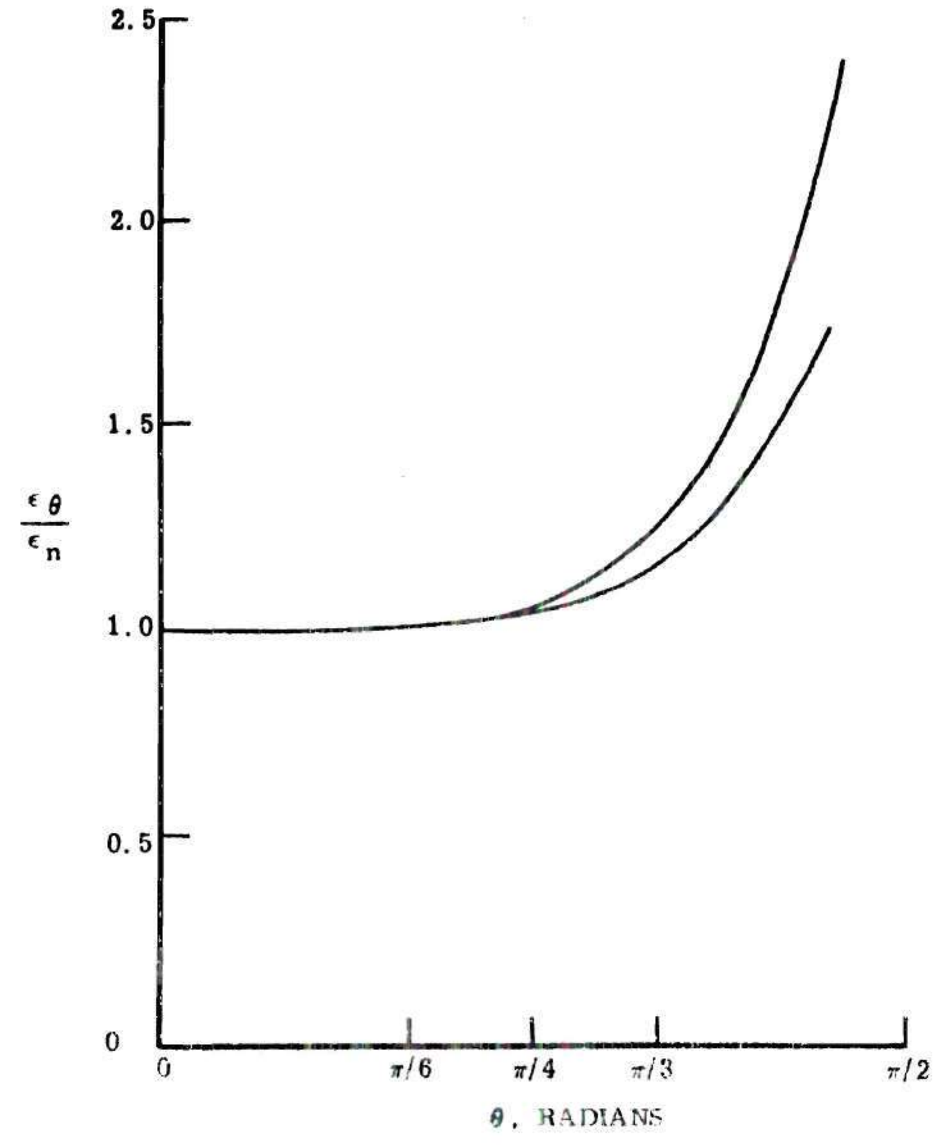


Figure 20. Relative Directional Emittance for Copper (Ref. 6)

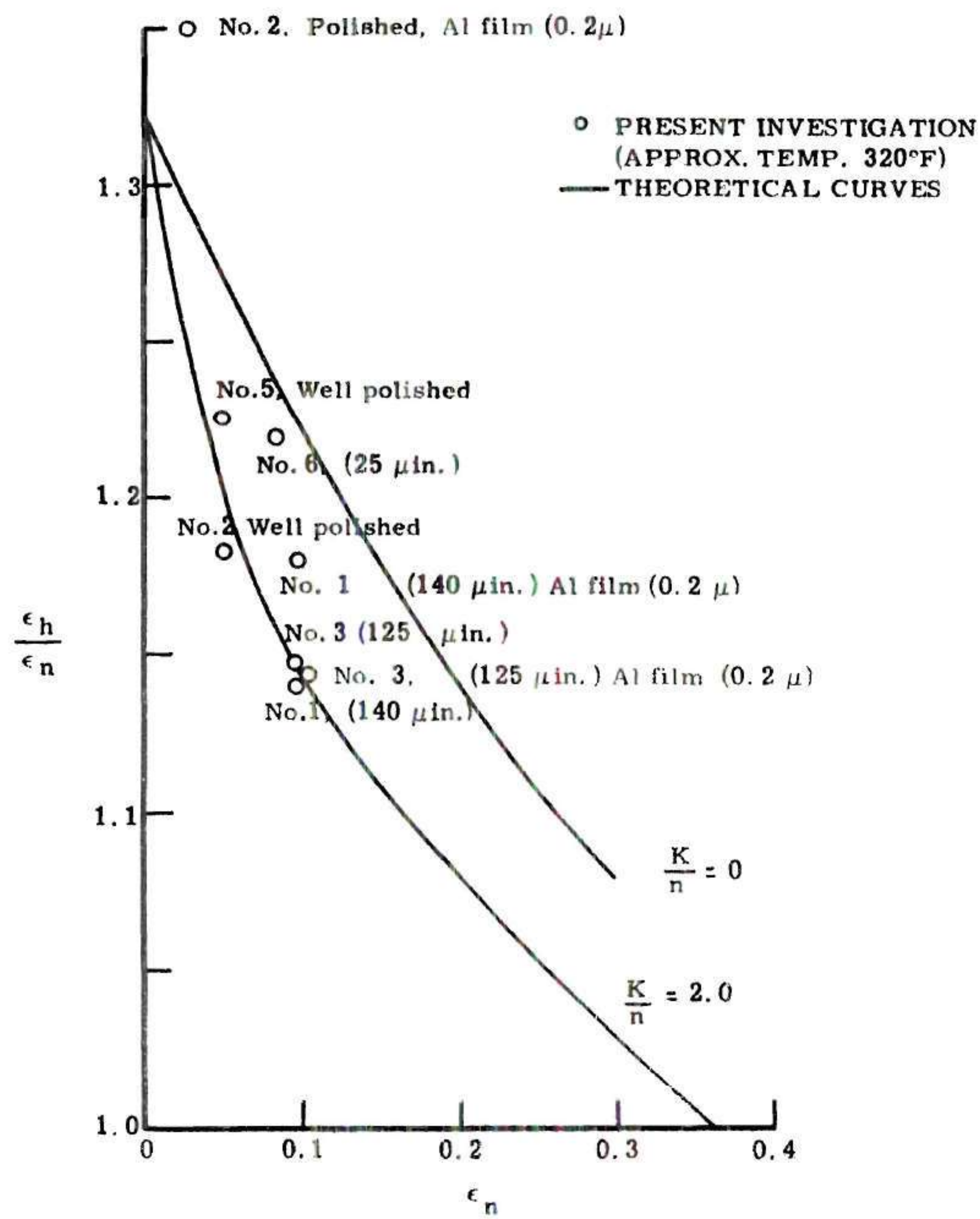


Figure 21. Theoretical and Experimental Values for the Ratio of Hemispherical to Normal Emissivity (Ref. 9)

APPENDIX E

HEMISPHERICAL EMITTANCE INTEGRAND OF VARIOUS SAMPLES

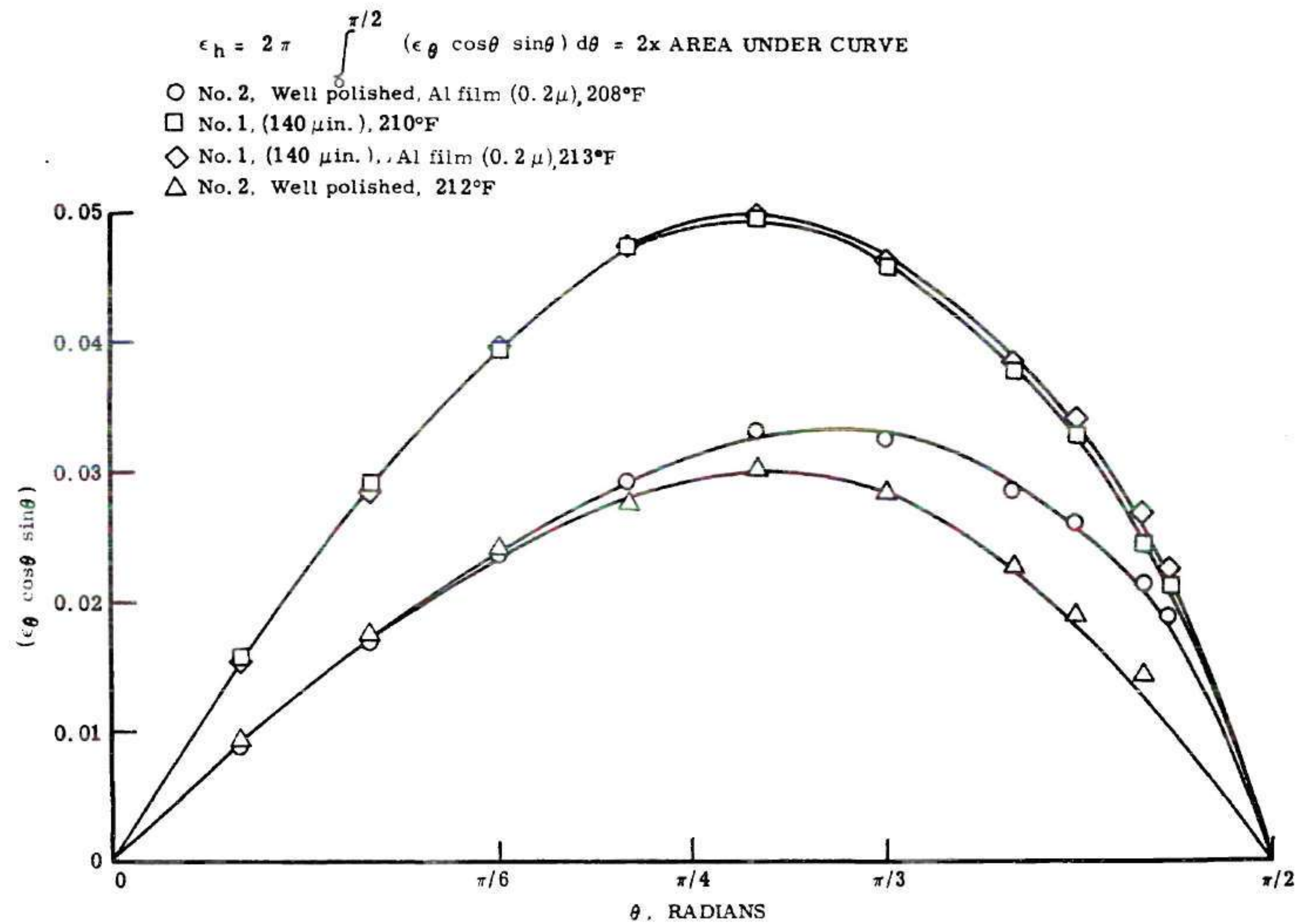


Figure 22. Hemispherical Emissivity Integrand

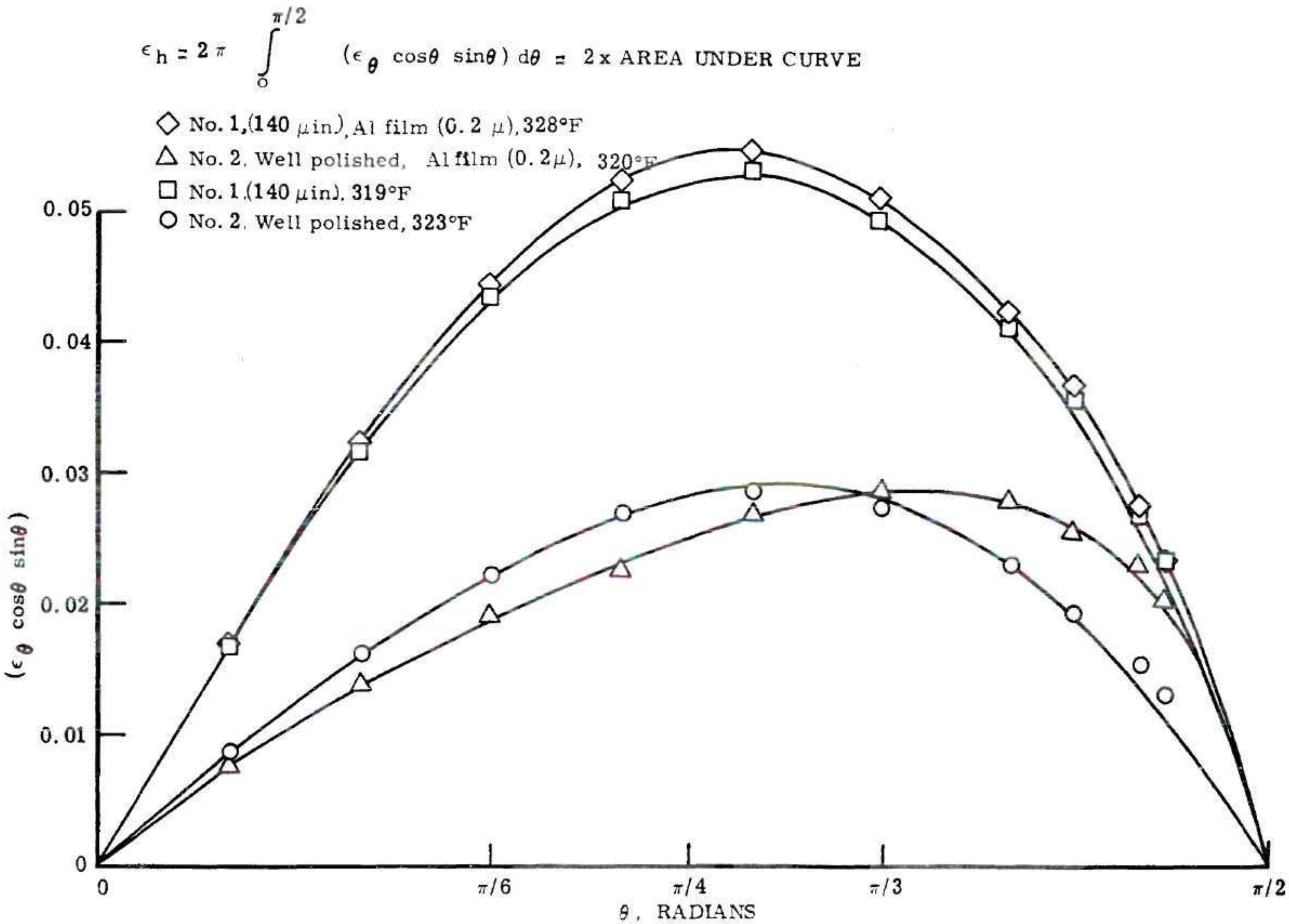


Figure 23. Hemispherical Emissivity Integrand

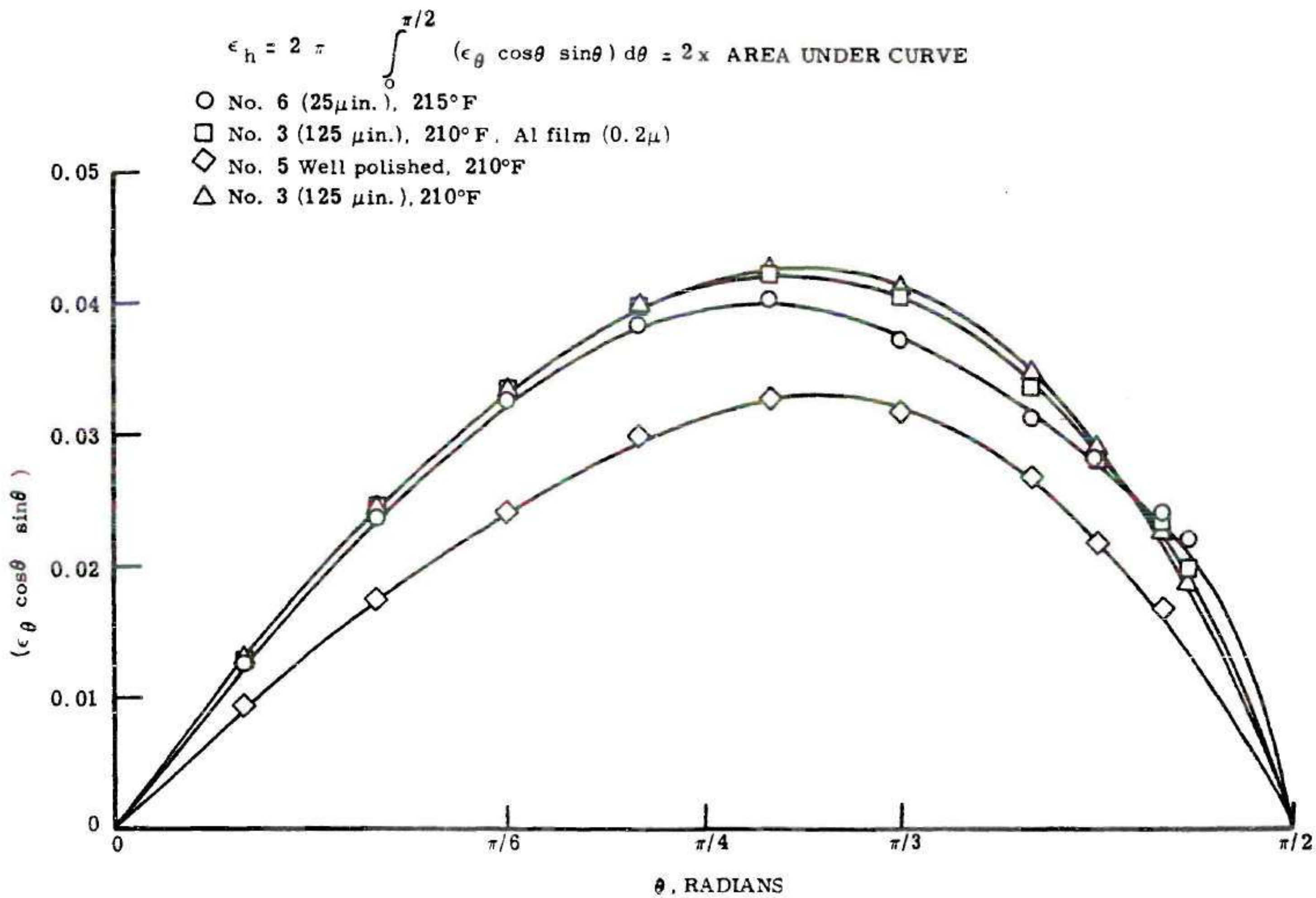


Figure 24 Hemispherical Emissivity Integrand

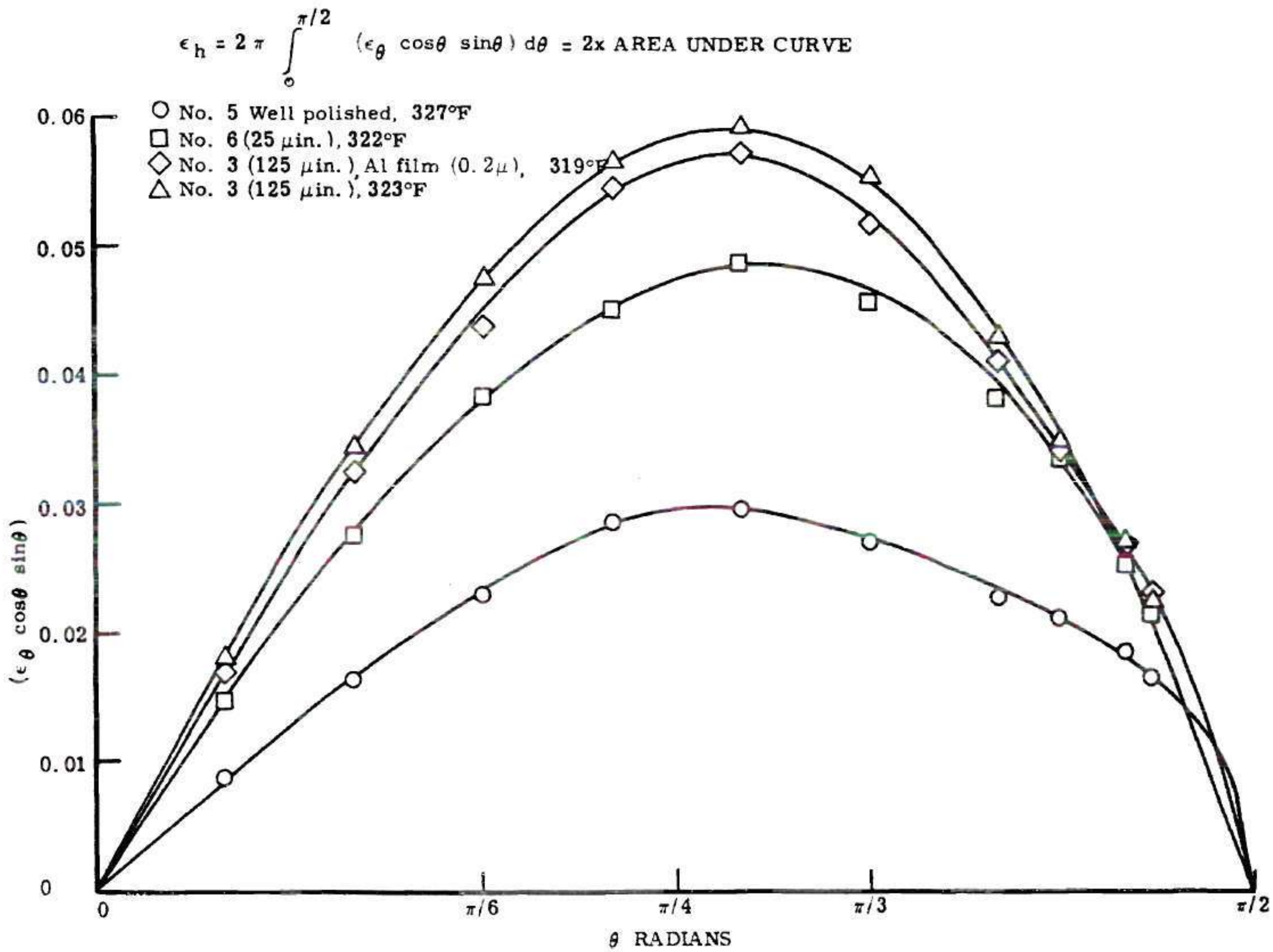


Figure 25. Hemispherical Emissivity Integrand

APPENDIX F

ERROR ANALYSIS

1. The heated blackbody temperature error is taken to be $\pm 1°F$. Since five thermocouples were located inside the blackbody, and were adjusted within $\pm 1°F$ of each other. The blackbody temperature was then taken as the average temperature shown by all thermocouples. Hence the maximum possible error from the average temperature of blackbody would be $\pm 1°F$.

2. The guard (blackbody) temperature error is taken to be $\pm 1°F$. Water was circulated to the guard from the water pipes. As the temperature of the outside atmosphere changes, slight change of temperature of circulating water was noticed. Hence, the maximum measured error in the guard temperature is taken as $\pm 1°F$.

3. The sample temperature error is taken to be $\pm 3°F$. Since the thermocouple was located at a distance less than $\frac{1}{32}$ inch from the test surface and since the thermal conductivity of aluminum is high, the maximum possible error from the calculation of the heat flux is $\pm 3°F$.

4. The accuracy of K-3 potentiometer for low range is $\pm 0.015\%$ of the reading + 0.5 microvolts. Since $\pm 0.015\%$ of the reading is negligible, hence, the possible error is taken to be ± 0.5 microvolts.

The maximum determinate error is then found as follows

$$\epsilon_{S\theta} = \frac{T_B^{\,4} - T_G^{\,4}}{T_S^{\,4} - T_G^{\,4}} \quad \frac{\Delta S_\theta}{\Delta B}$$

or

$$\ln \epsilon_{S\theta} = \ln (T_B^{\,4} - T_G^{\,4}) - \ln (T_S^{\,4} - T_G^{\,4}) + \ln (\Delta S_\theta) - \ln (\Delta B)$$

and differentiating, using finite sums and absolute values

$$\frac{\delta(\epsilon_{S\theta})}{\epsilon_{S\theta}} = \frac{\delta(T_B^{\,4} - T_G^{\,4})}{(T_B^{\,4} - T_G^{\,4})} + \frac{\delta(T_S^{\,4} - T_G^{\,4})}{(T_S^{\,4} - T_G^{\,4})} + \frac{\delta(\Delta S_\theta)}{\Delta S_\theta} + \frac{\delta(\Delta B)}{\Delta B}$$

Substituting in above equation basis values and errors stated above, and using data used for sample calculation (Appendix A)

$$\frac{\delta(\epsilon_{S\theta})}{\epsilon_{S\theta}} = \frac{11.64}{453.24} + \frac{64.68}{3004.62} + \frac{0.5}{22.0} + \frac{0.5}{30.04}$$

$$= 2.56\% + 2.15\% + 2.27\% + 1.66\%$$

$$= 8.64\%$$

The maximum determinate error is

$$\frac{\delta(\epsilon_{S\theta})}{\epsilon_{S\theta}} = \pm\, 8.64\%$$

$$\delta(\epsilon_{S\theta}) = \pm\, 0.0103$$

This would correspond to

$$\epsilon_{S\theta} = 0.119 \pm 0.0103$$

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